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Ahmed et al.

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(45) **Date of Patent: Jan. 12, 2016**

(54) **APPARATUS AND METHOD FOR VOLTAGE AND CURRENT BALANCING IN GENERATION OF OUTPUT POWER IN POWER GENERATION SYSTEMS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/446,277**

(22) Filed: **Jul. 29, 2014**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
H02J 3/46 (2006.01)
H02J 3/38 (2006.01)

(52) **U.S. Cl.**
CPC . ***H02J 3/382*** (2013.01); ***H02J 3/46*** (2013.01); *Y10T 307/691* (2015.04)

(58) **Field of Classification Search**
CPC Y10T 307/707; Y10T 307/685; Y10T 307/691; H02J 3/46; H02J 3/382
USPC 307/77, 78, 82
See application file for complete search history.

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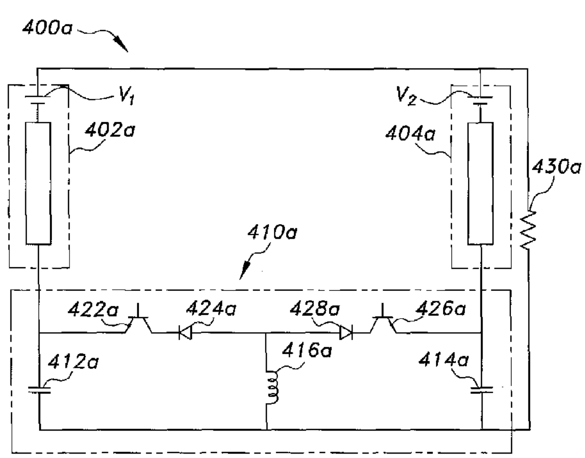
Primary Examiner — Fritz M Fleming
(74) *Attorney, Agent, or Firm* — Richard C. Litman

(57) **ABSTRACT**

An apparatus for voltage balancing parallel arranged direct current (DC) voltage source strings in a power generation system includes a string voltage balancing circuit having reverse blocking switches to control a current flow and an output voltage of the DC voltage source strings. Capacitors are connected to a corresponding reverse blocking switch and in series with a corresponding one of the plurality of DC voltage source strings to construct a voltage difference for a corresponding one of the plurality DC voltage source strings. The string voltage balancing circuit adjusts an output voltage of the DC voltage source strings by controlling a current flowing in the plurality of DC voltage source strings to adjust a voltage constructed across corresponding ones of the capacitors to balance the output voltage for the DC voltage source strings to be substantially the same output voltage. Current balancing using differential power processing is also provided.

20 Claims, 32 Drawing Sheets



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Morsy et al., A New Approach for Increasing Energy Harvest in Large Scale PV Plants Employing a Novel Voltage Balancing Topology, 6 pages, distributed Nov. 2013, IECON Conference, Nov. 10-13, 2013.

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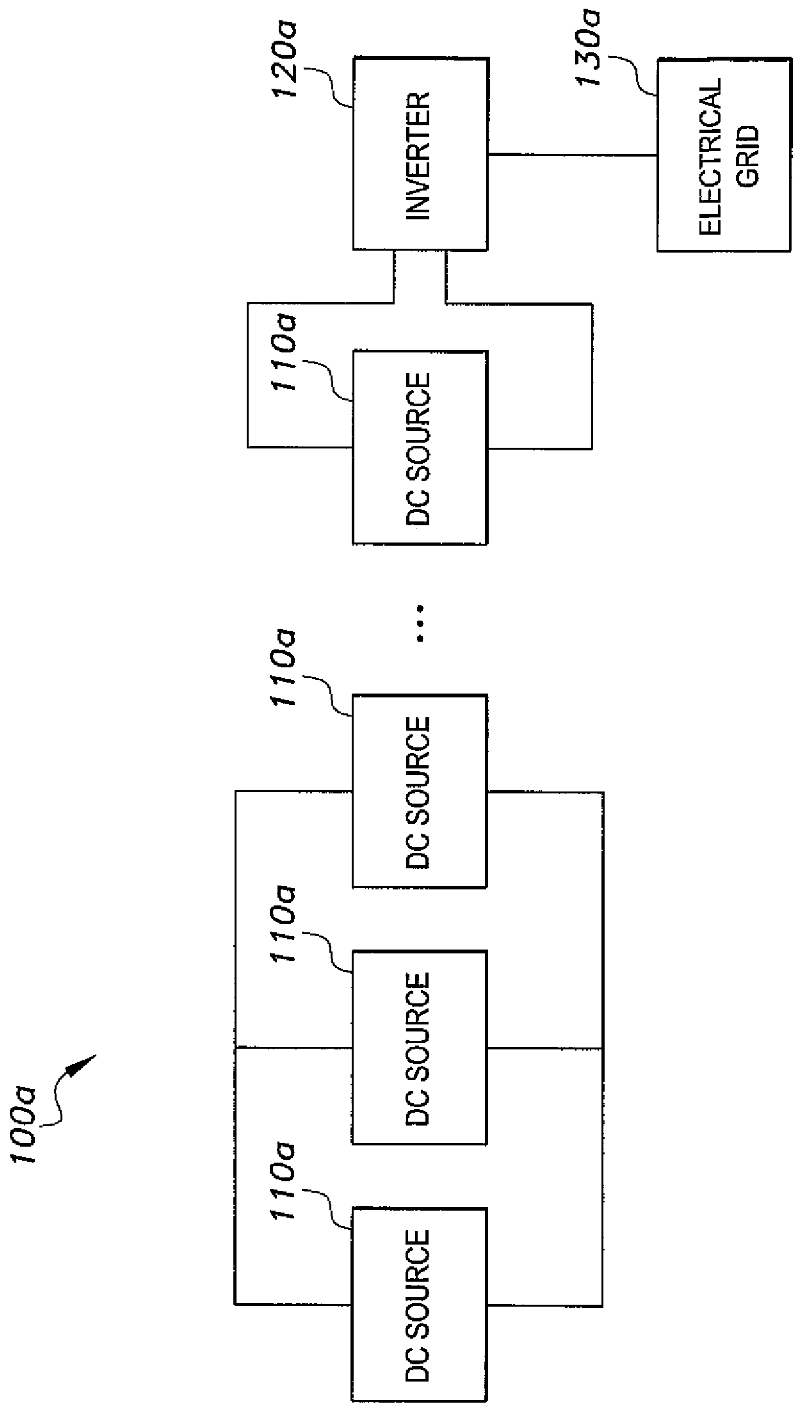

100a
110a
DC SOURCE
110a
DC SOURCE
110a
DC SOURCE
110a
DC SOURCE
120a
INVERTER
130a
ELECTRICAL GRID

Fig. 1A

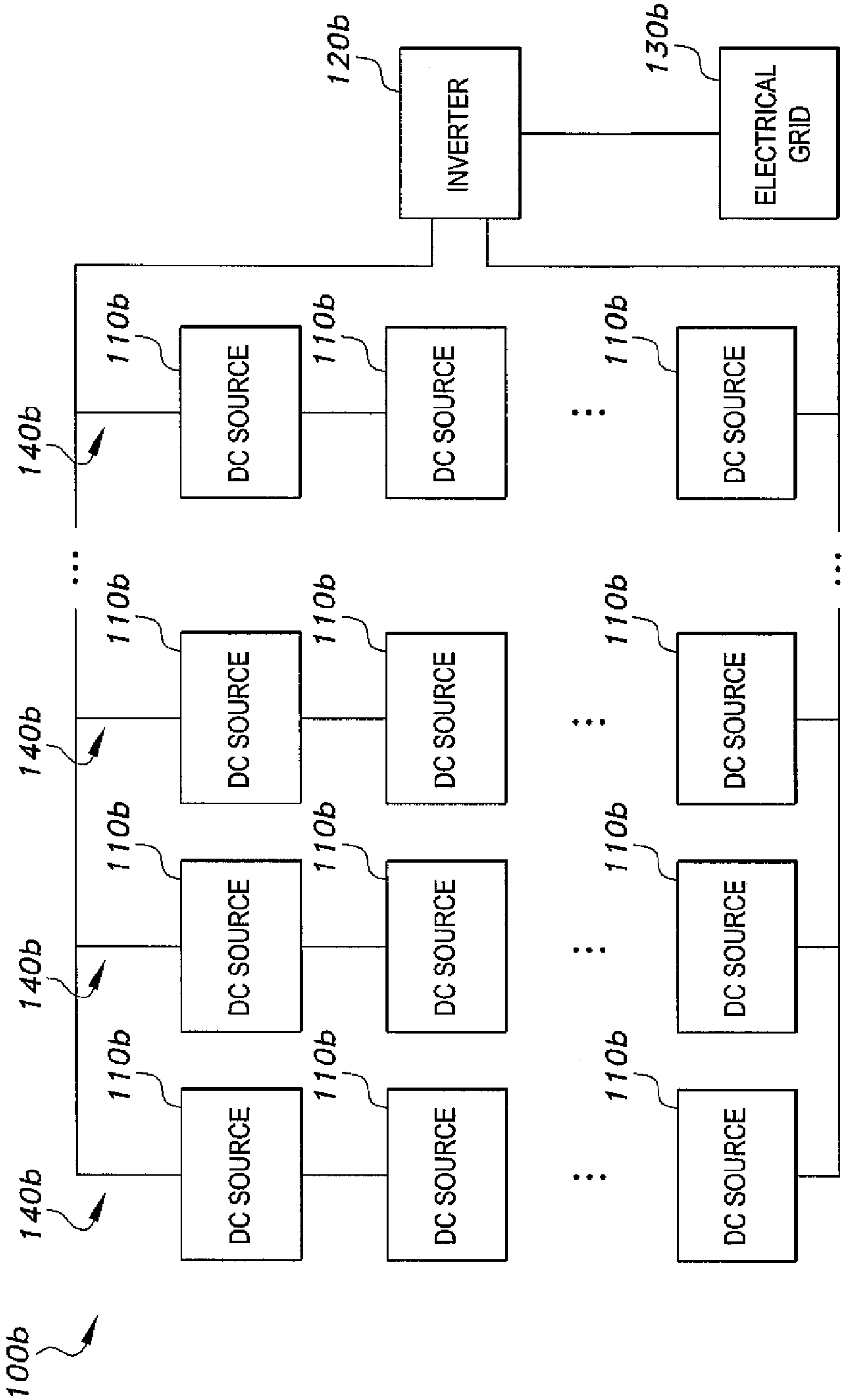

120b
INVERTER
130b
ELECTRICAL GRID
110b
DC SOURCE
140b
100b

Fig. 1B

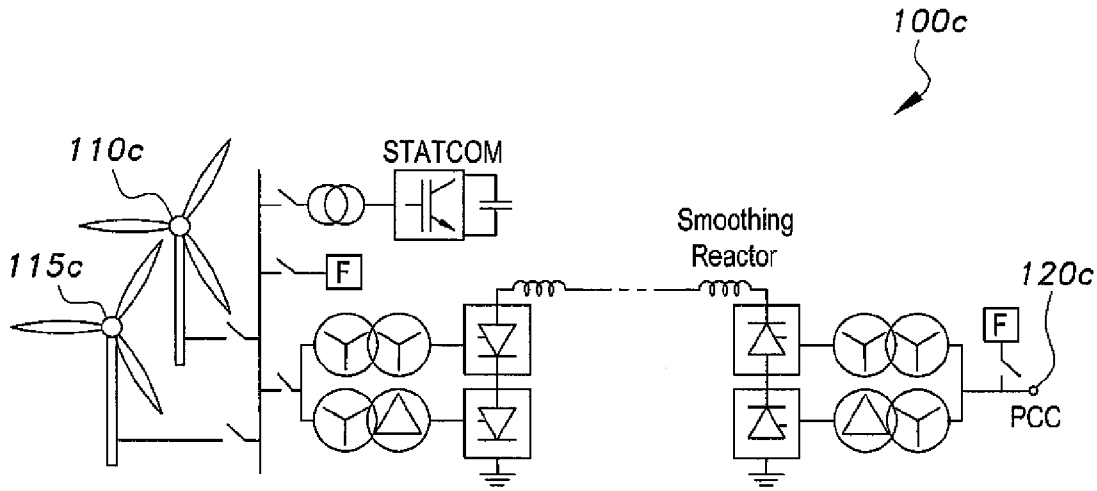

100c
110c
115c
STATCOM
F
Smoothing
Reactor
120c
F
PCC

Fig. 1C

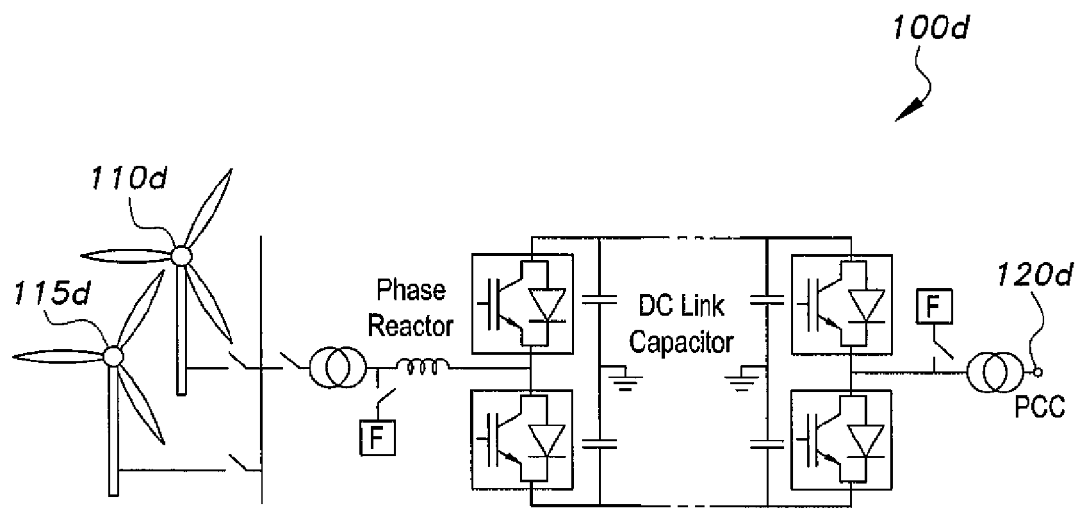

100d
110d
115d
Phase
Reactor
F
DC Link
Capacitor
120d
F
PCC

Fig. 1D

100e

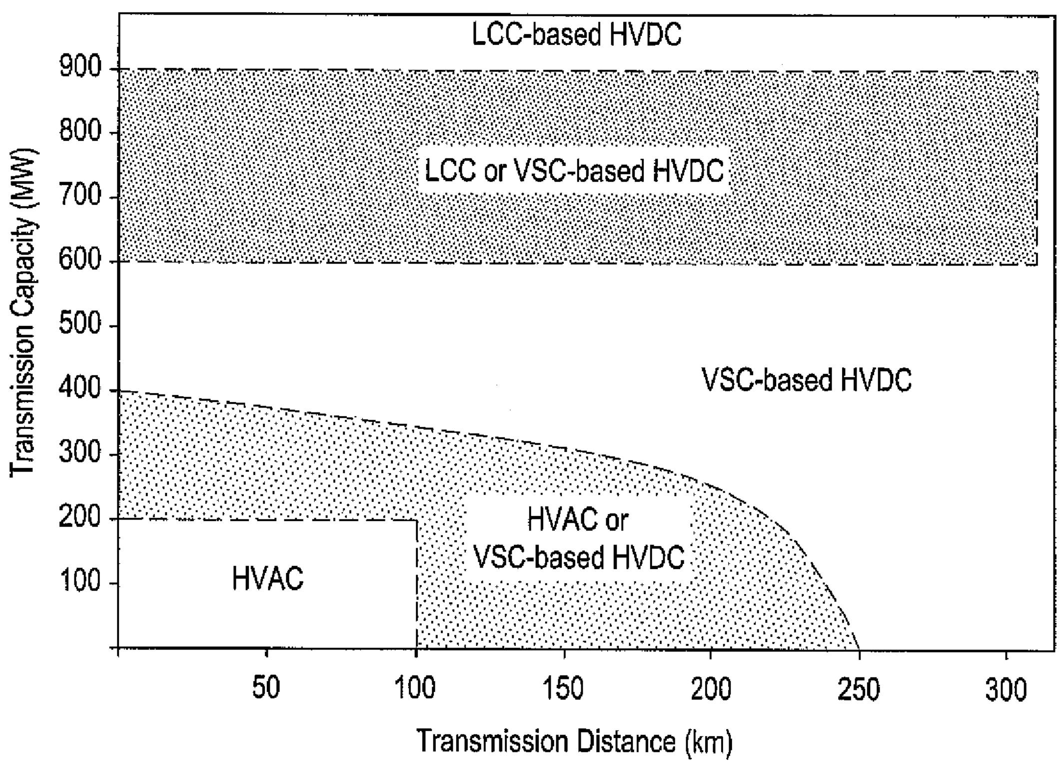

LCC-based HVDC
900
800
700
600
500
400
300
200
100
Transmission Capacity (MW)
LCC or VSC-based HVDC
VSC-based HVDC
HVAC or
VSC-based HVDC
HVAC
50
100
150
200
250
300
Transmission Distance (km)

Fig. 1E

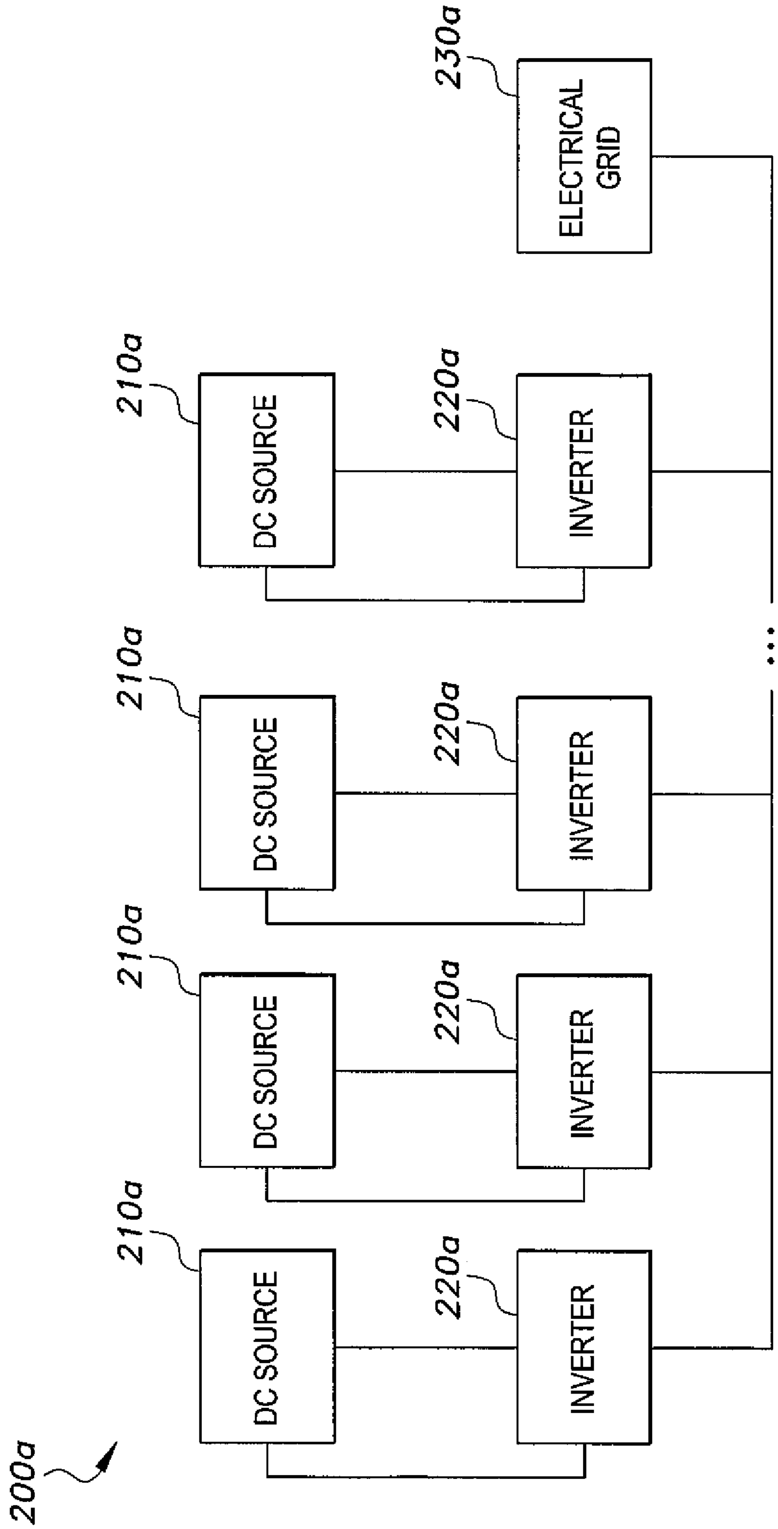

230a
ELECTRICAL GRID
210a
DC SOURCE
220a
INVERTER
210a
DC SOURCE
220a
INVERTER
210a
DC SOURCE
220a
INVERTER
210a
DC SOURCE
220a
INVERTER
200a

Fig. 2A

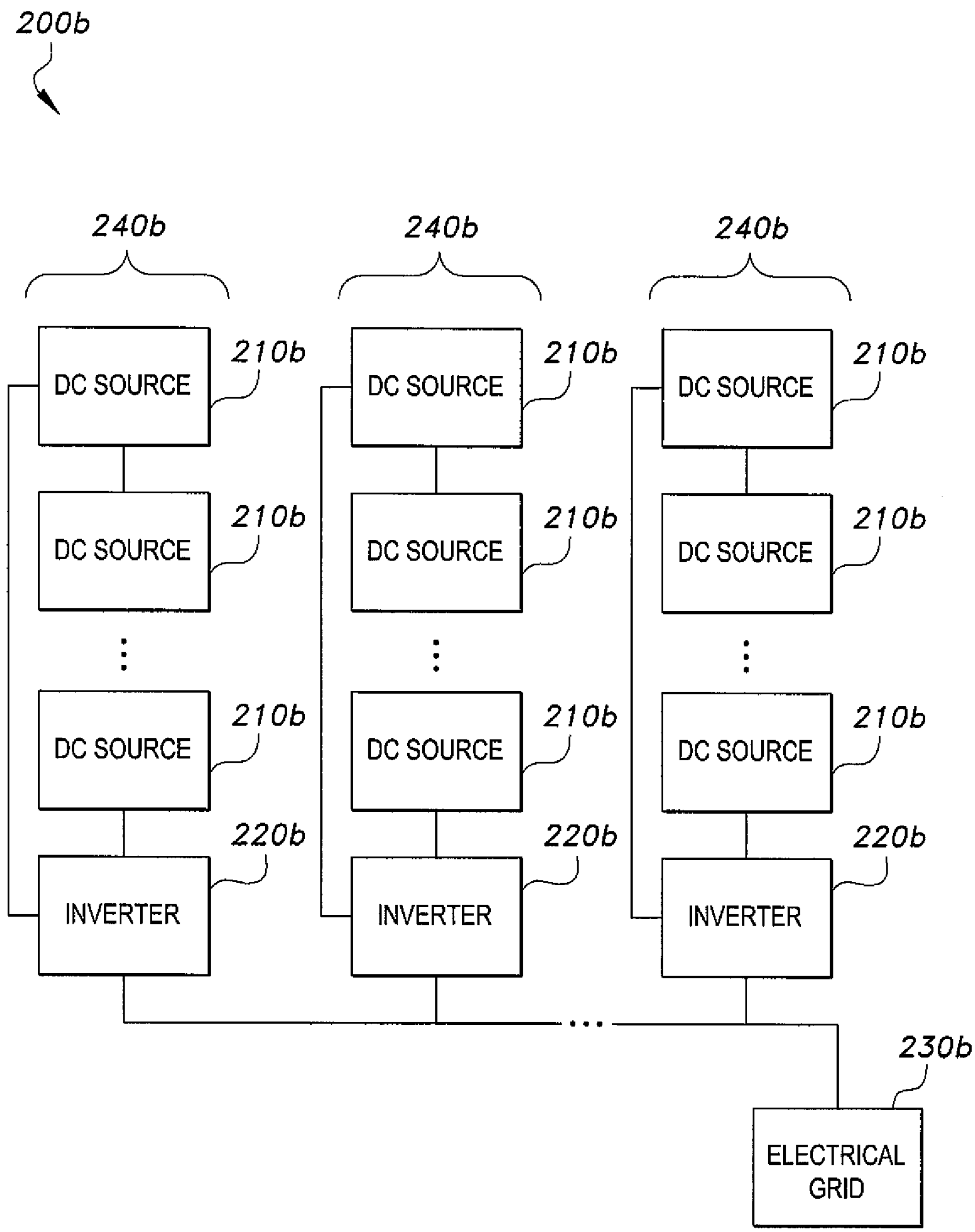

200b
240b
240b
240b
DC SOURCE
210b
DC SOURCE
210b
DC SOURCE
210b
DC SOURCE
210b
DC SOURCE
210b
DC SOURCE
210b
DC SOURCE
210b
DC SOURCE
210b
DC SOURCE
210b
INVERTER
220b
INVERTER
220b
INVERTER
220b
230b
ELECTRICAL GRID

Fig. 2B

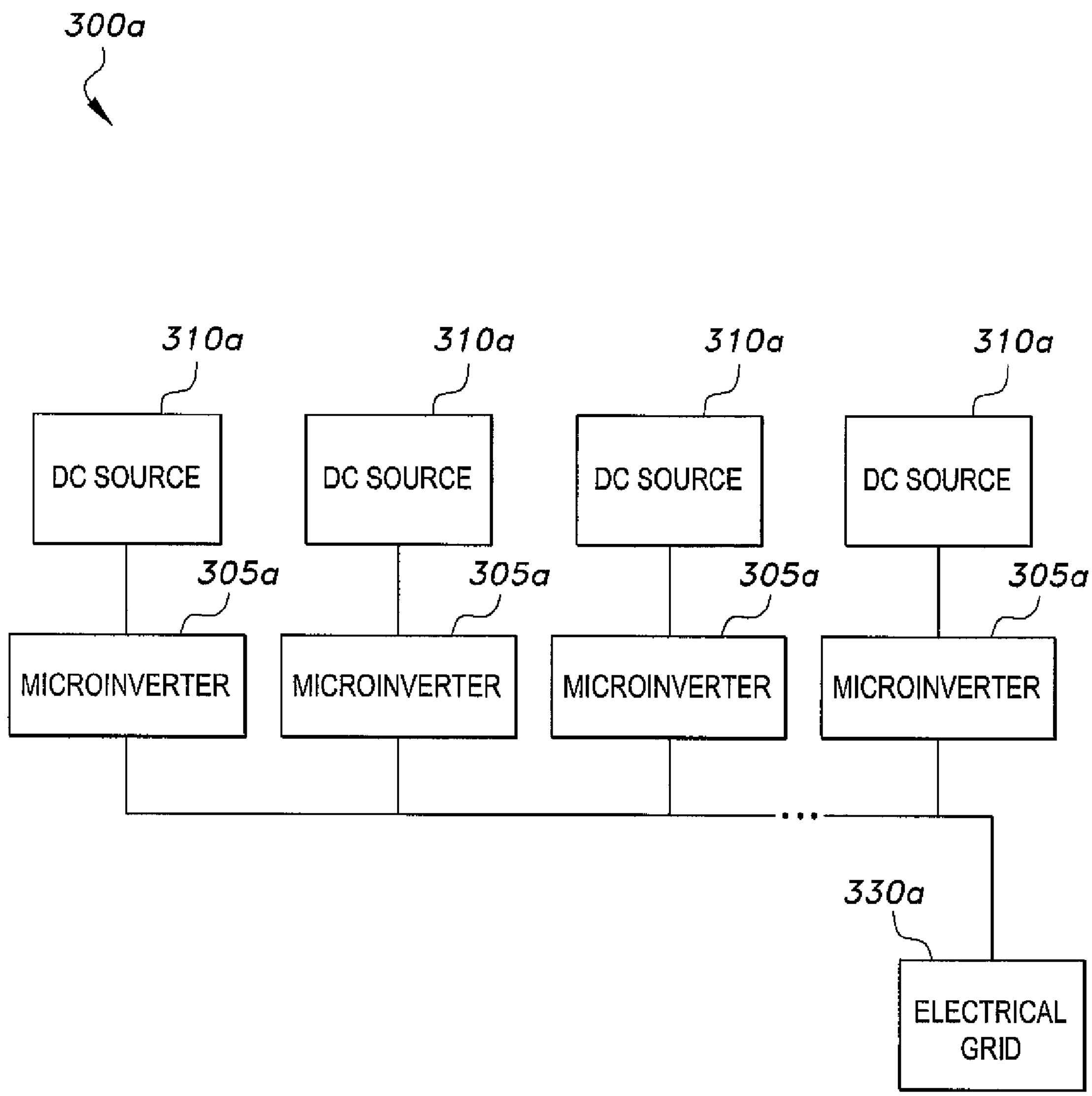

300a
310a
DC SOURCE
310a
DC SOURCE
310a
DC SOURCE
310a
DC SOURCE
305a
MICROINVERTER
305a
MICROINVERTER
305a
MICROINVERTER
305a
MICROINVERTER
330a
ELECTRICAL GRID

Fig. 3A

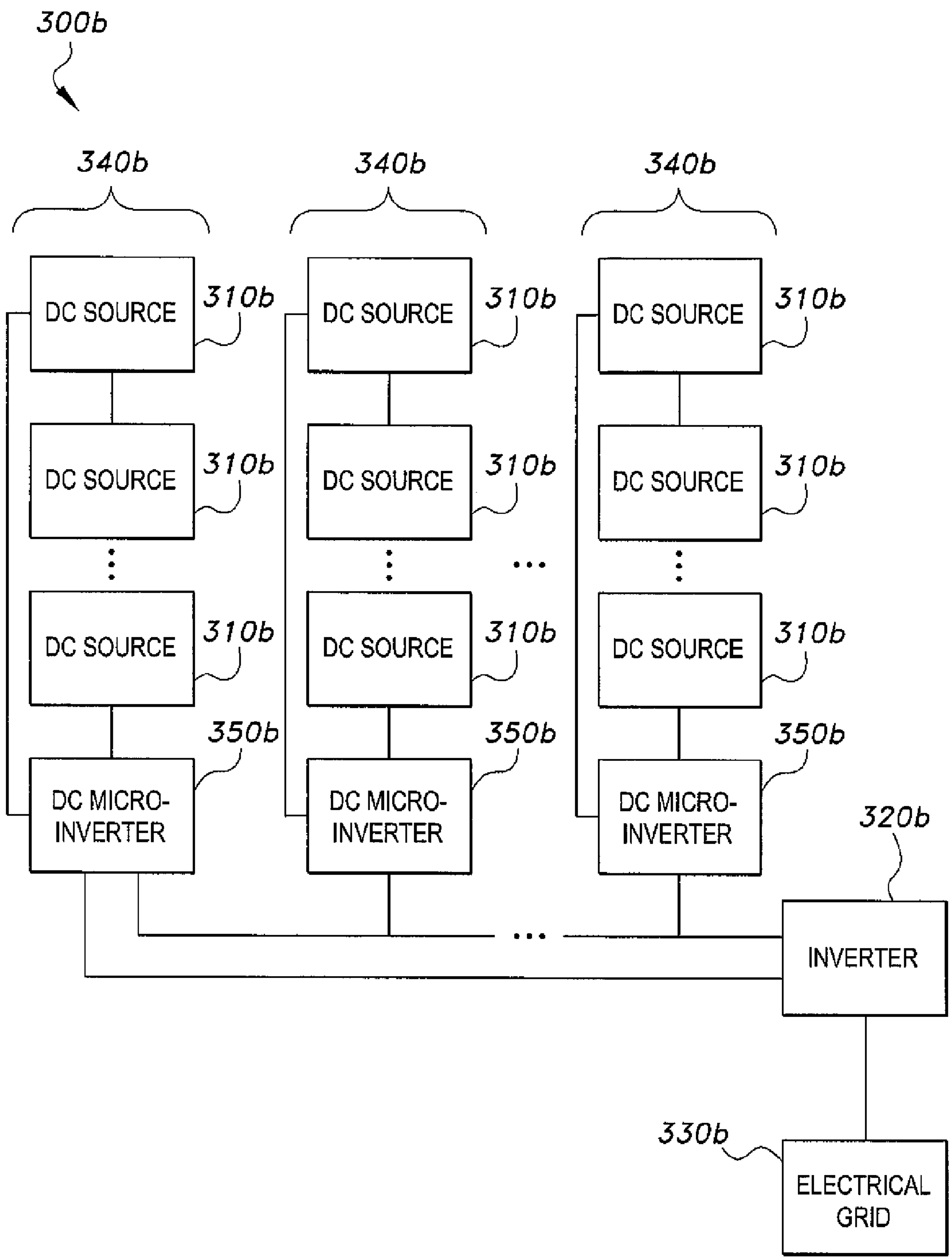

300b
340b
340b
340b
DC SOURCE
310b
DC SOURCE
310b
DC SOURCE
310b
DC SOURCE
310b
DC SOURCE
310b
DC SOURCE
310b
DC SOURCE
310b
DC SOURCE
310b
DC SOURCE
310b
350b
DC MICRO-INVERTER
350b
DC MICRO-INVERTER
350b
DC MICRO-INVERTER
320b
INVERTER
330b
ELECTRICAL GRID

Fig. 3B

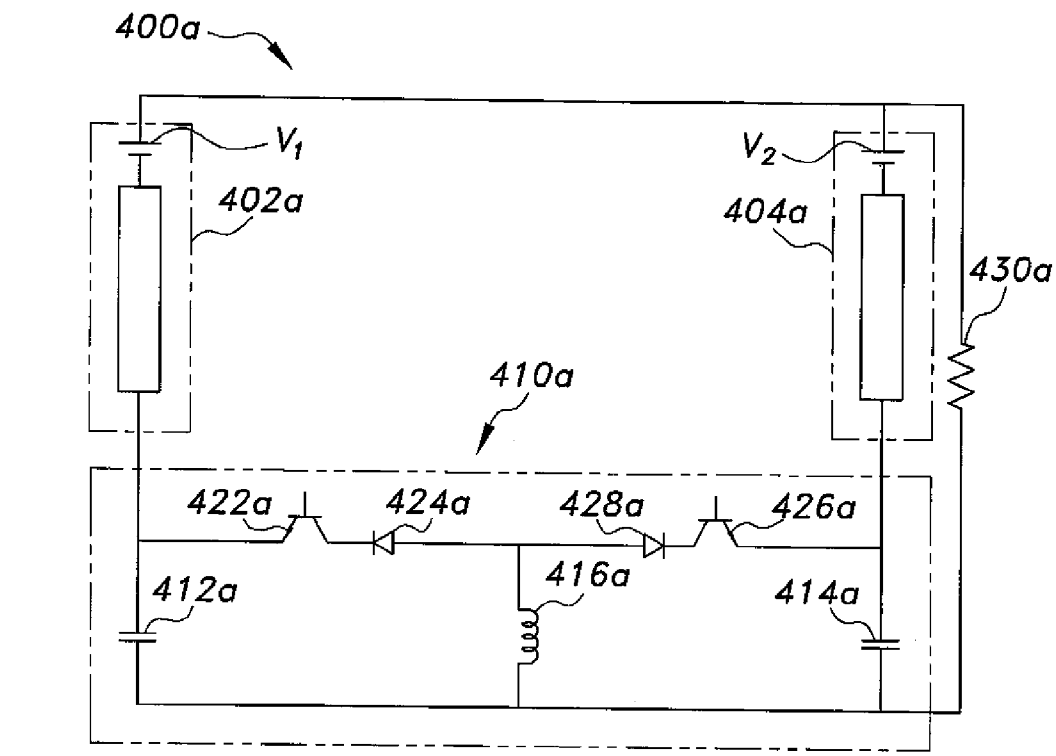

400a
V1
402a
V2
404a
430a
410a
422a
424a
428a
426a
416a
412a
414a

Fig. 4A

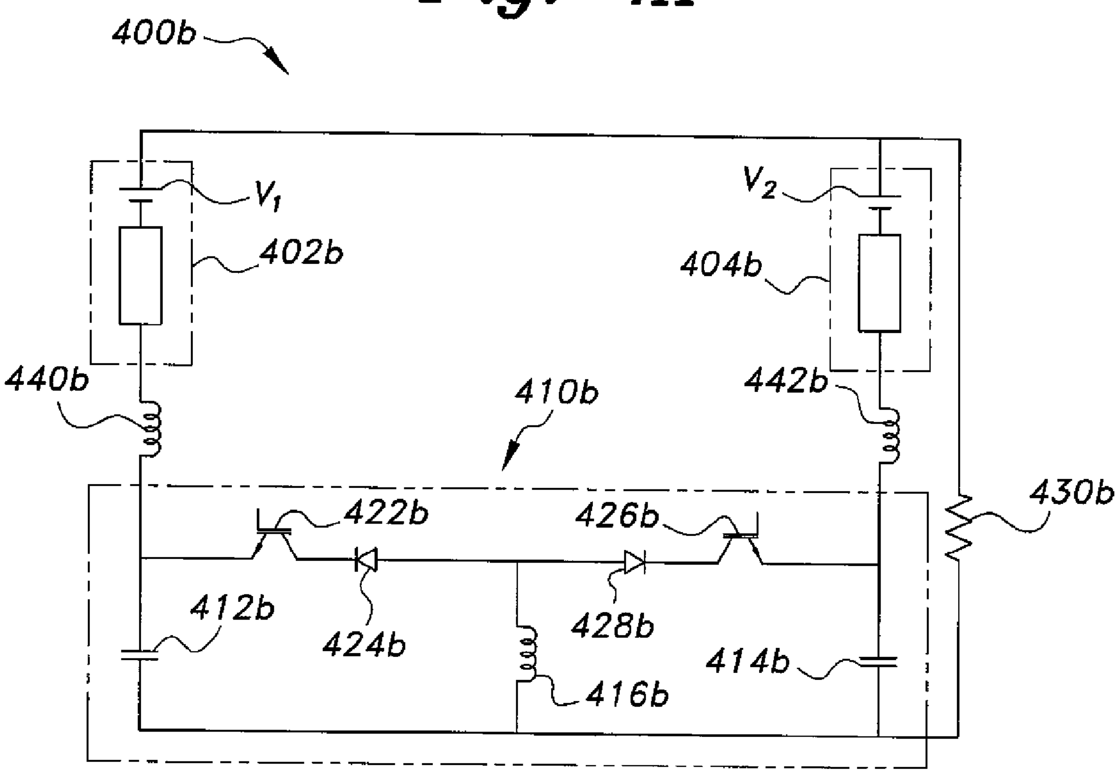

400b
V1
402b
V2
404b
440b
410b
442b
422b
426b
430b
412b
424b
428b
414b
416b

Fig. 4B

400c

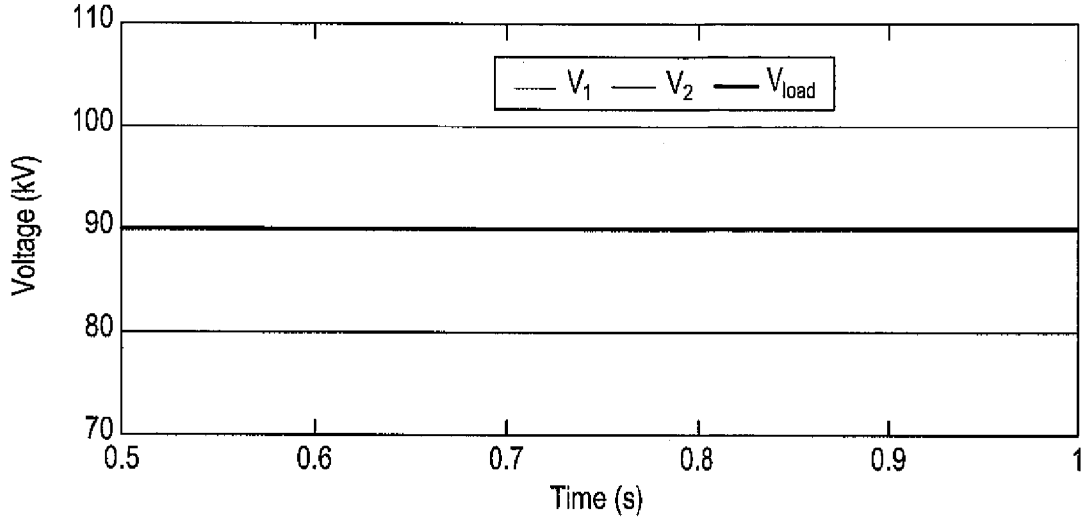


Fig. 4C

400d

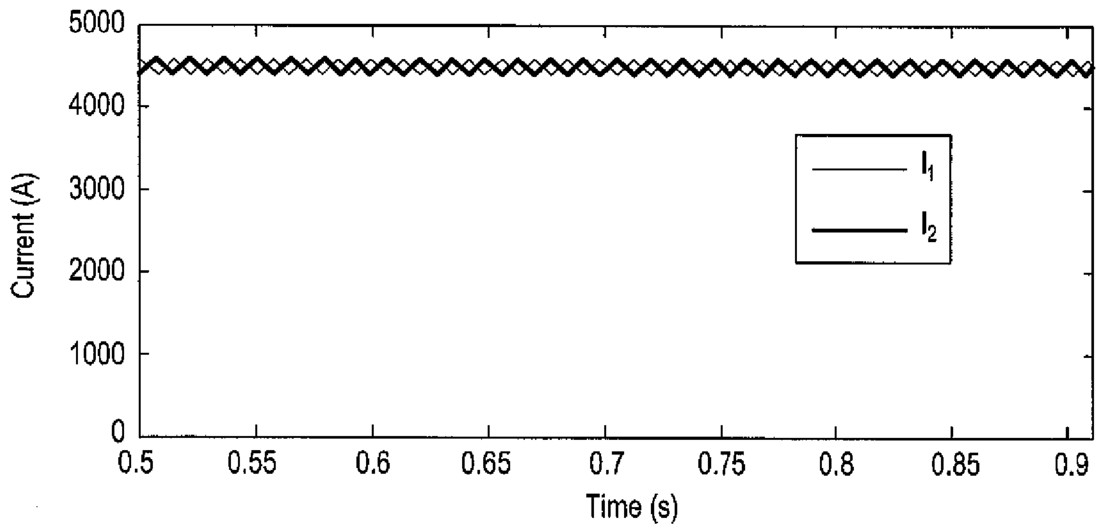


Fig. 4D

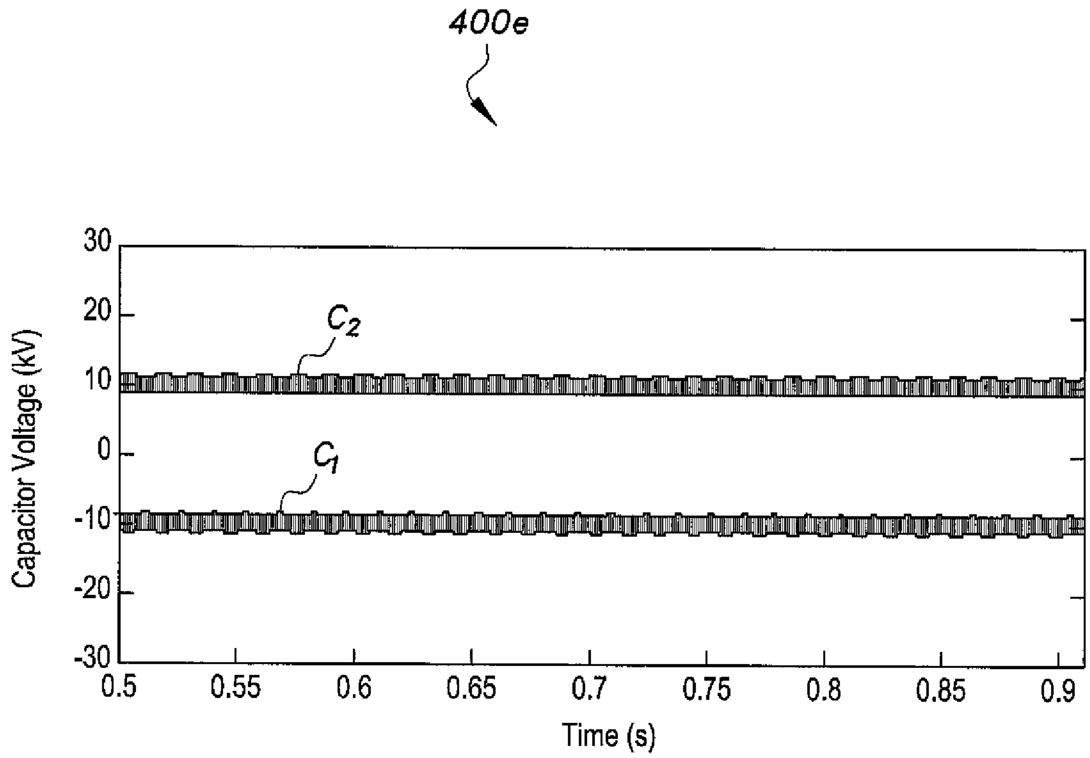

400e
30
20
10
0
-10
-20
-30
Capacitor Voltage (kV)
C2
C1
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
Time (s)

Fig. 4E

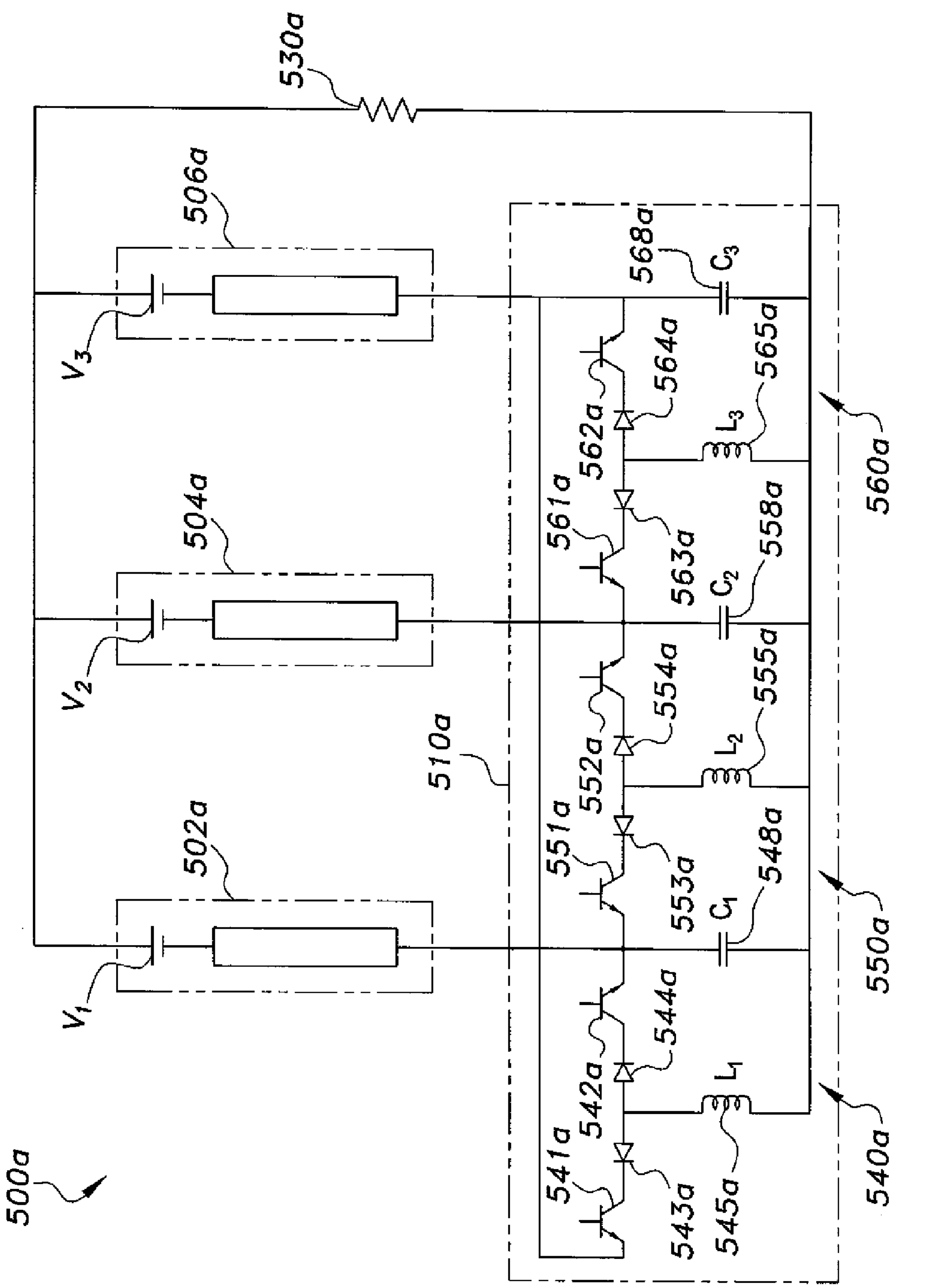
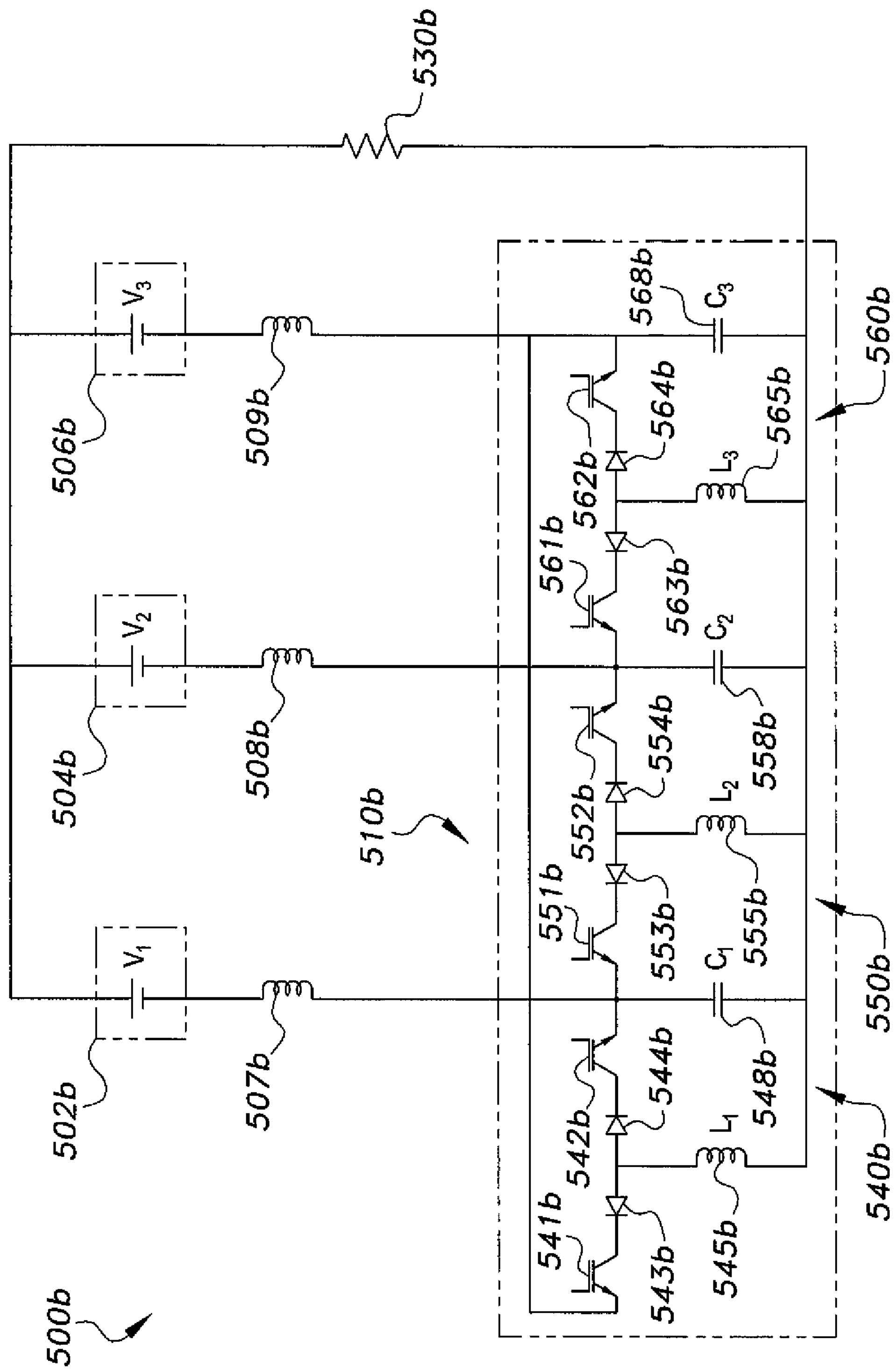

500a
530a
502a
504a
506a
510a
V_1
V_2
V_3
541a
542a
543a
544a
545a
L_1
540a
548a
C_1
551a
552a
553a
554a
555a
L_2
550a
558a
C_2
561a
562a
563a
564a
565a
L_3
560a
568a
C_3

Fig. 5A



530b
506b
509b
568b
V_3
C_3
560b
564b
565b
562b
L_3
561b
563b
504b
V_2
C_2
508b
554b
558b
552b
L_2
510b
551b
555b
553b
502b
V_1
C_1
507b
544b
548b
550b
542b
L_1
541b
545b
543b
540b
500b

Fig. 5B

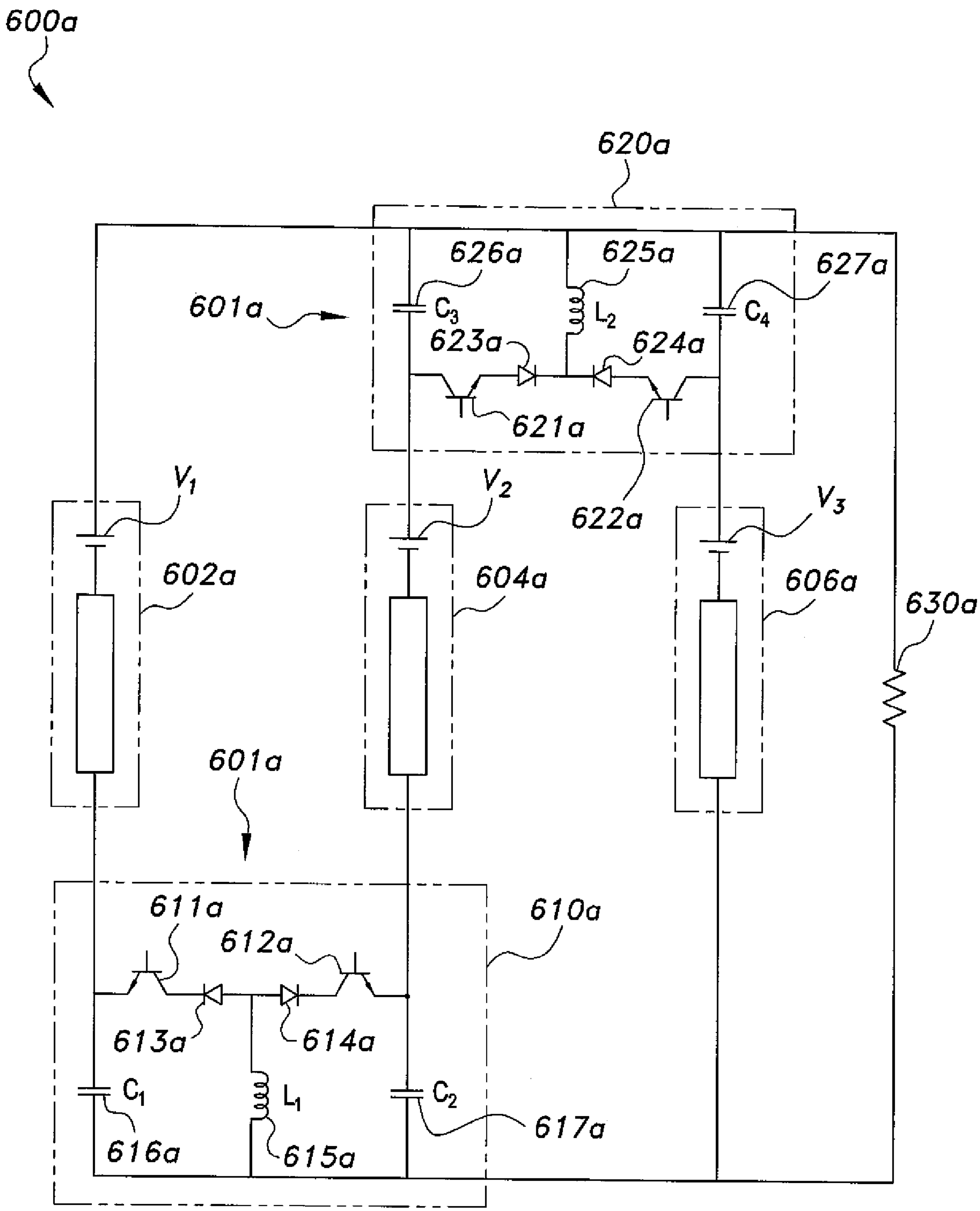

600a
620a
626a
625a
627a
601a
C3
L2
C4
623a
624a
621a
622a
V1
V2
V3
602a
604a
606a
630a
601a
610a
611a
612a
613a
614a
C1
L1
C2
617a
616a
615a

Fig. 6A

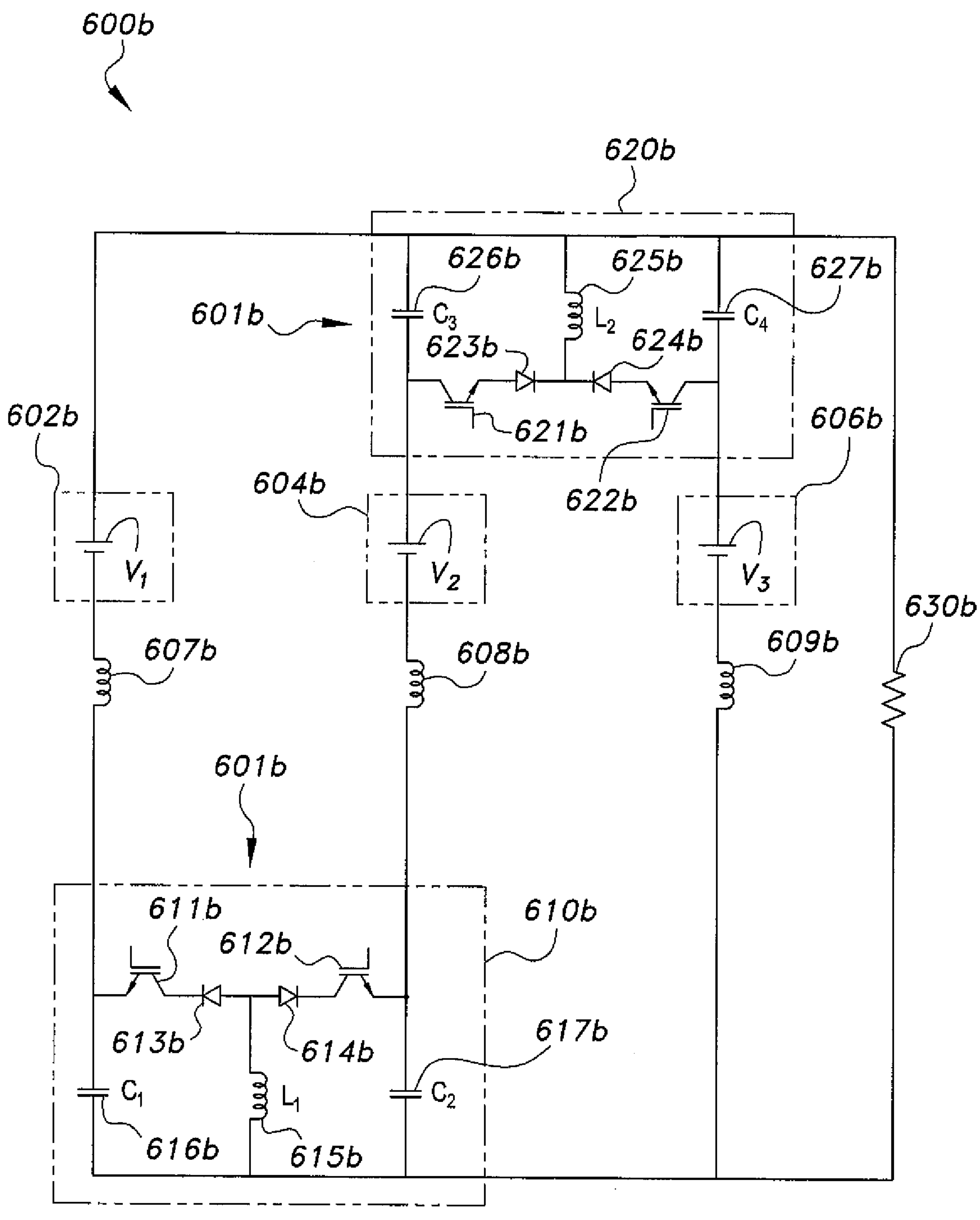

600b
620b
626b
625b
627b
601b
C_3
L_2
C_4
623b
624b
621b
602b
606b
604b
622b
V_1
V_2
V_3
630b
607b
608b
609b
601b
611b
610b
612b
613b
614b
617b
C_1
L_1
C_2
616b
615b

Fig. 6B

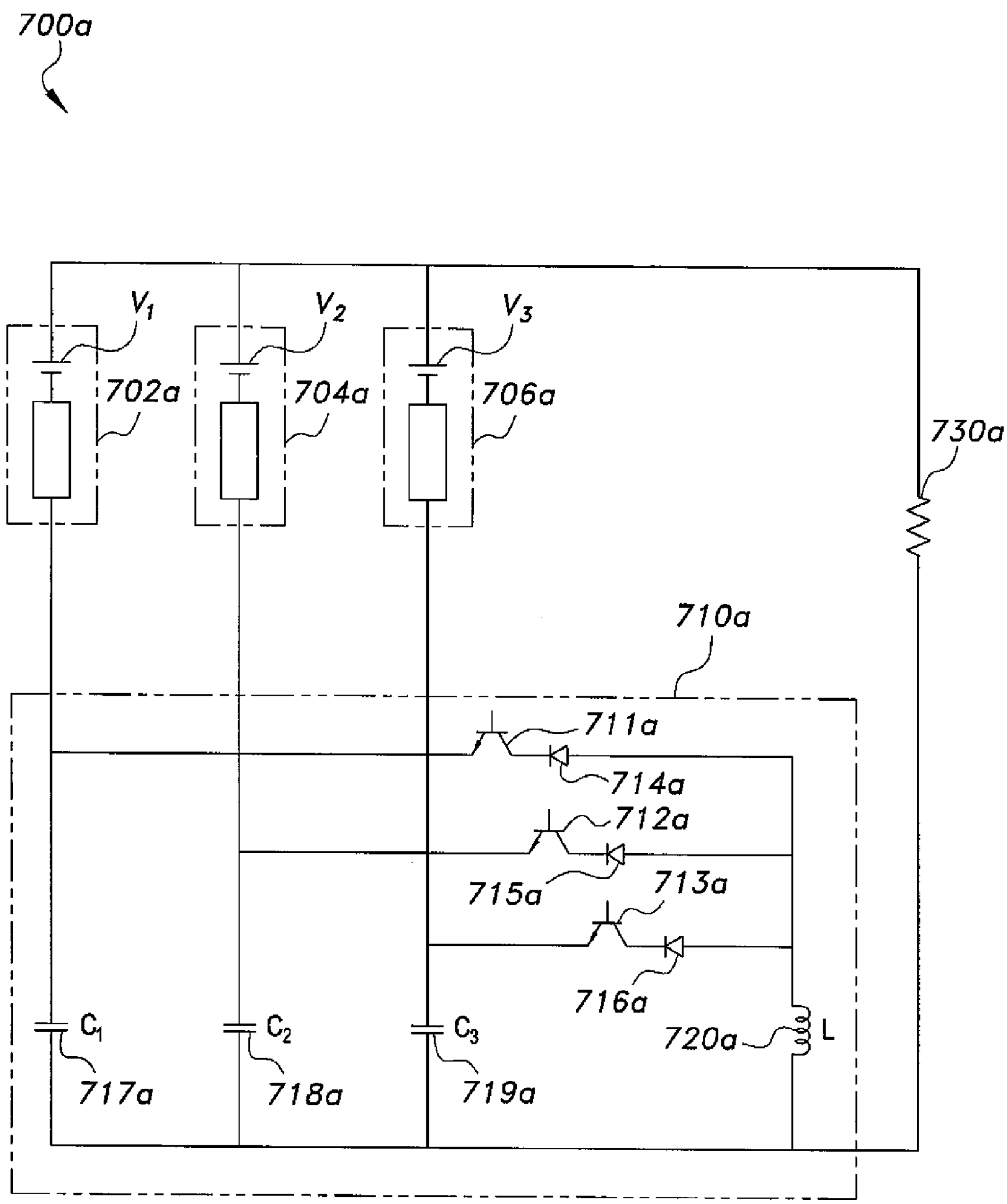

700a
V1
V2
V3
702a
704a
706a
730a
710a
711a
714a
712a
715a
713a
716a
C1
C2
C3
720a
L
717a
718a
719a

Fig. 7A

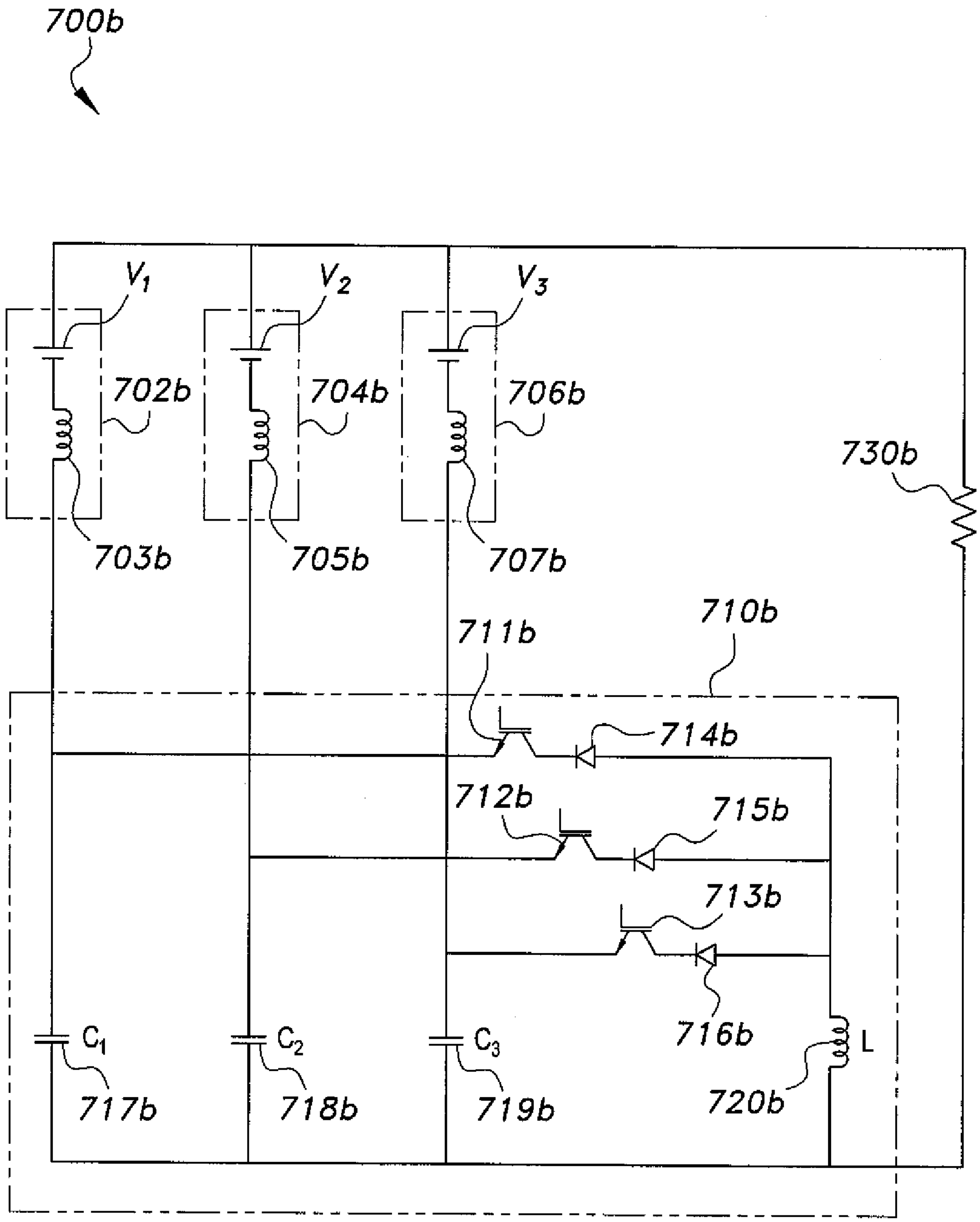

700b
V1
V2
V3
702b
704b
706b
703b
705b
707b
730b
710b
711b
714b
712b
715b
713b
716b
C1
C2
C3
L
717b
718b
719b
720b

Fig. 7B

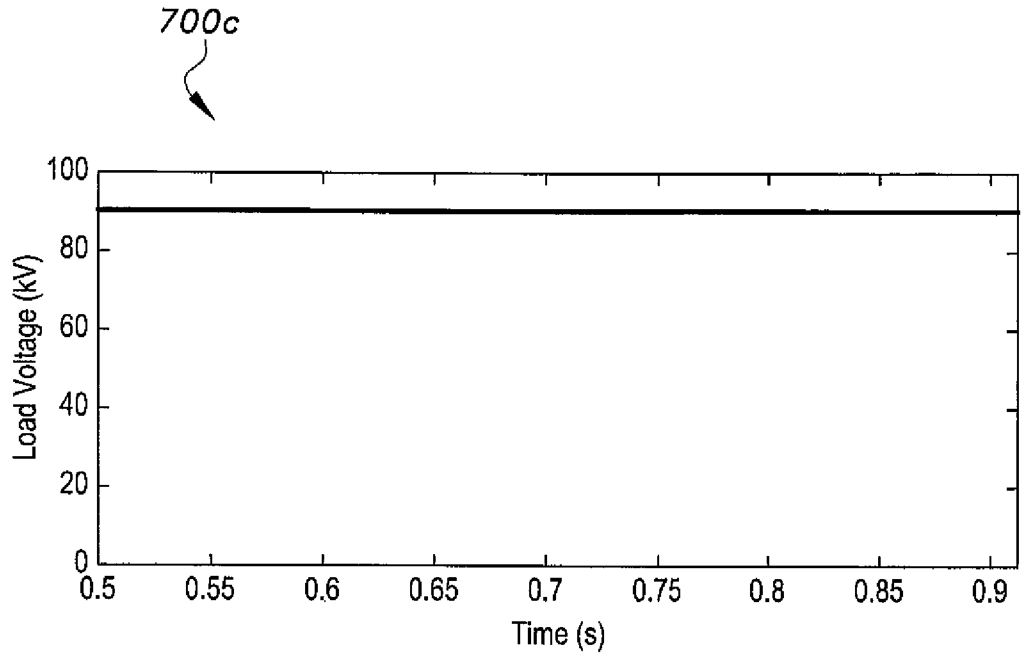

700c
100
80
60
40
20
0
Load Voltage (kV)
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
Time (s)

Fig. 7C

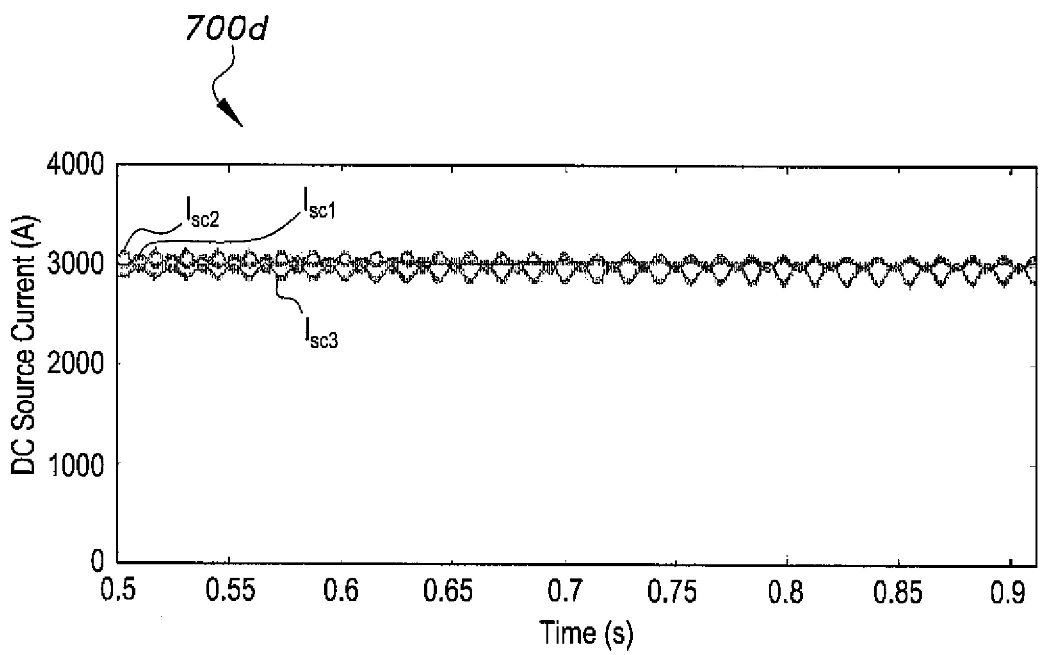

700d
4000
3000
2000
1000
0
DC Source Current (A)
I_{sc2}
I_{sc1}
I_{sc3}
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
Time (s)

Fig. 7D

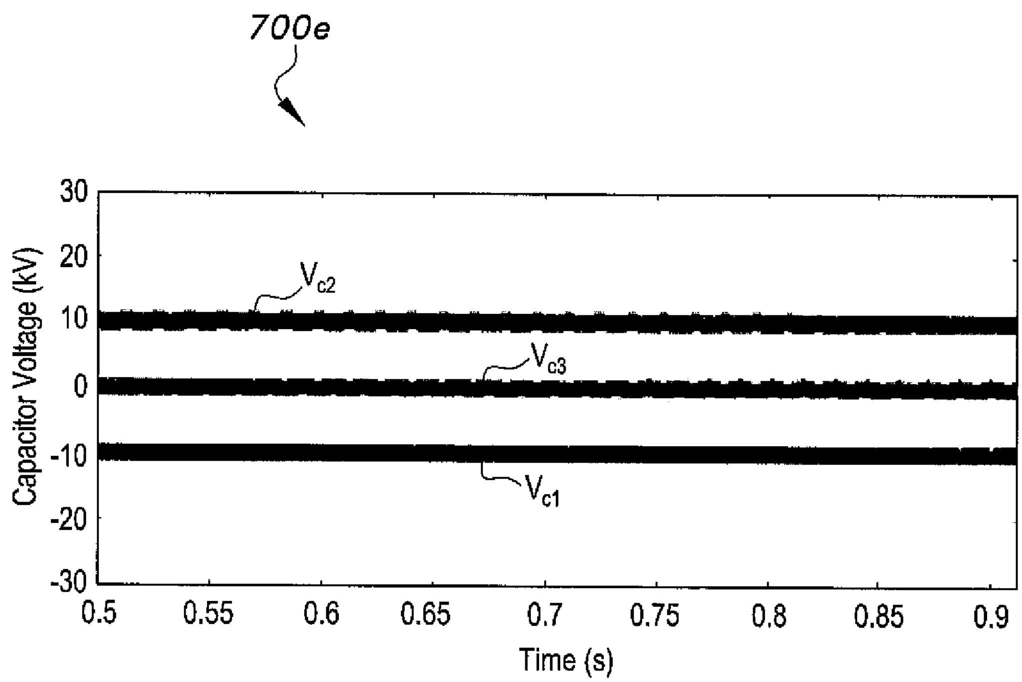

700e
30
20
10
0
-10
-20
-30
Capacitor Voltage (kV)
V_{c2}
V_{c3}
V_{c1}
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
Time (s)

Fig. 7E

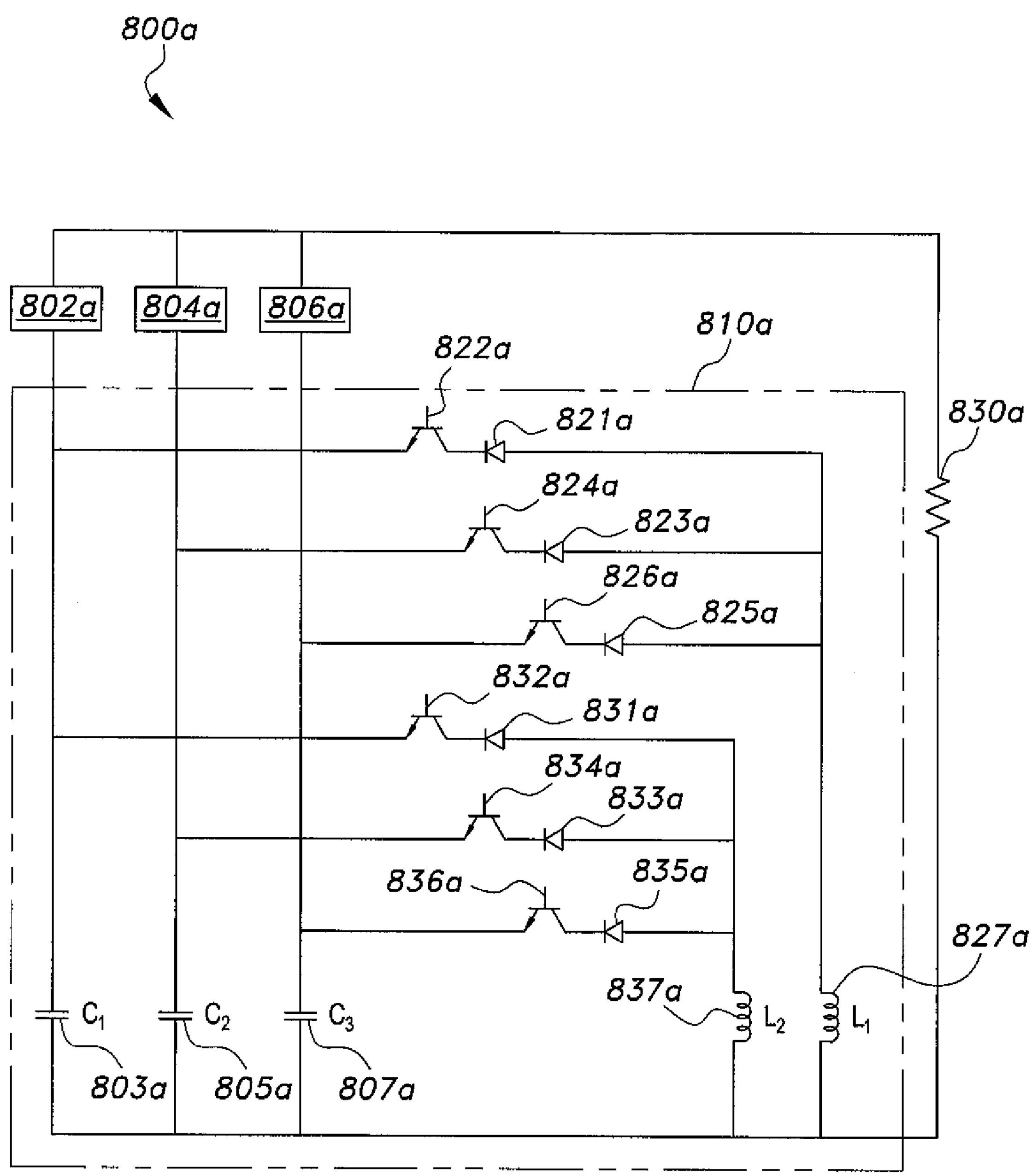
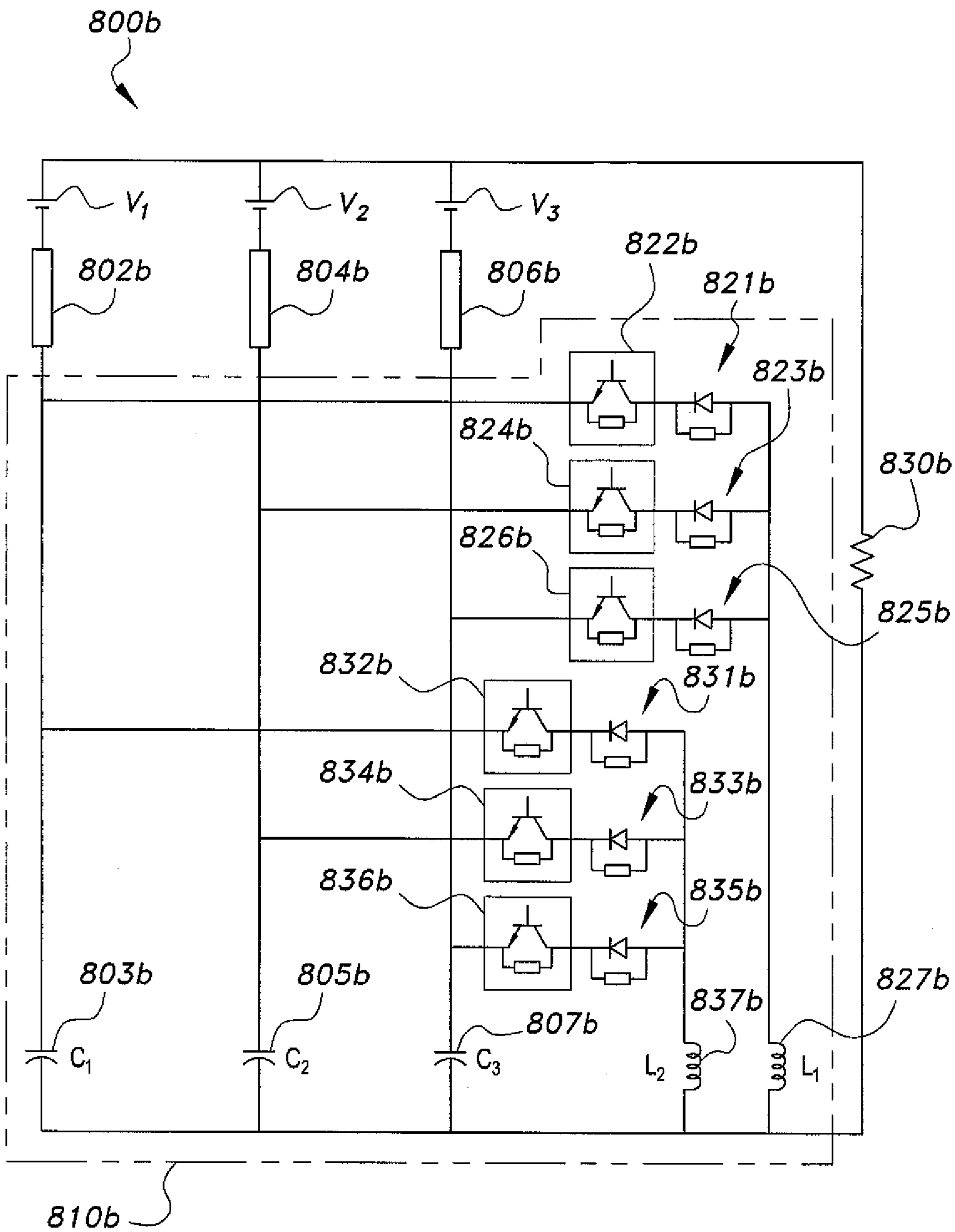

800a
802a
804a
806a
810a
822a
821a
830a
824a
823a
826a
825a
832a
831a
834a
833a
836a
835a
827a
837a
C1
C2
C3
L2
L1
803a
805a
807a

Fig. 8A


800b
V1
V2
V3
802b
804b
806b
822b
821b
823b
824b
826b
830b
825b
832b
831b
834b
833b
836b
835b
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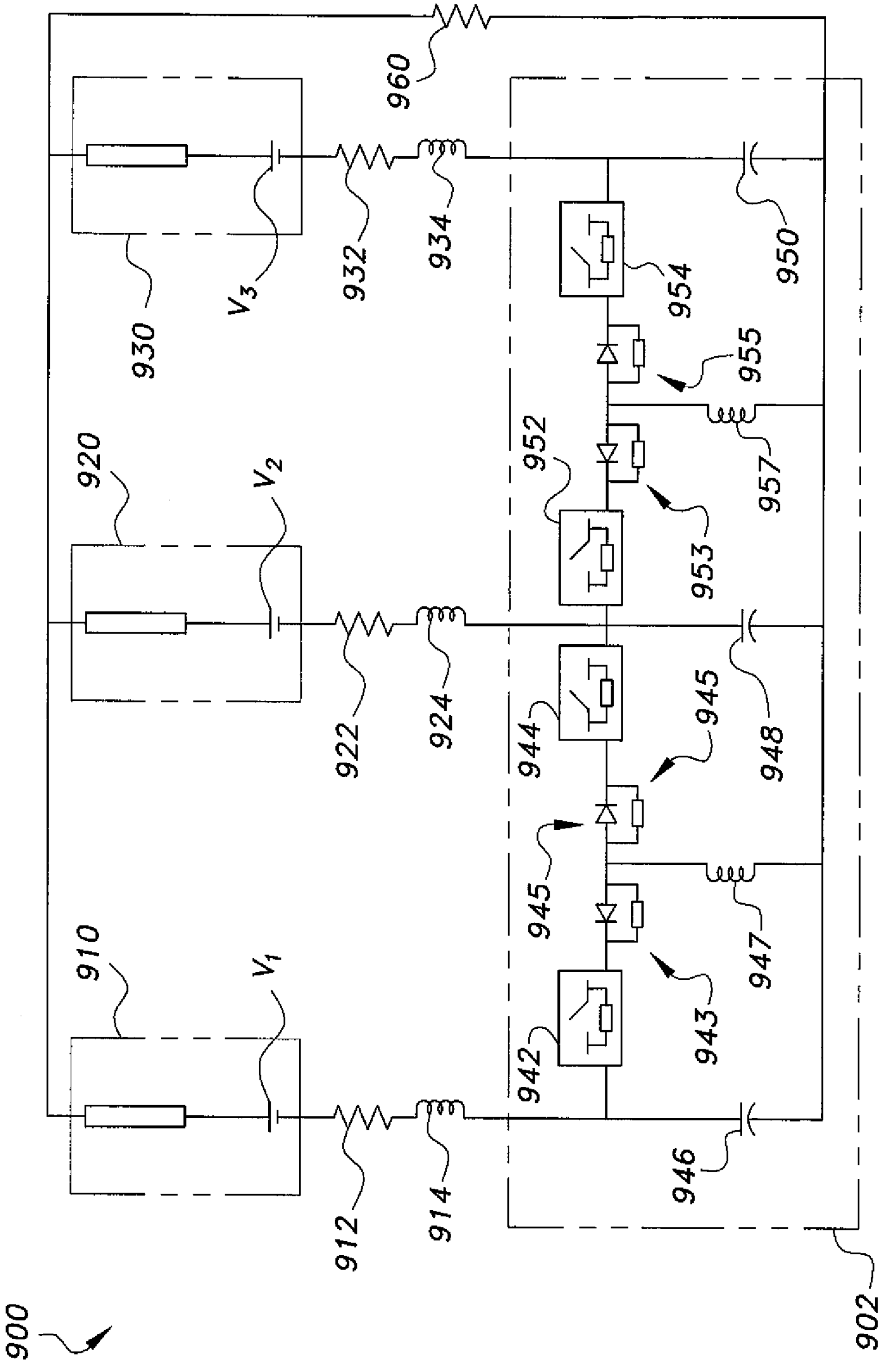
805b
807b
837b
827b
C1
C2
C3
L2
L1
810b

Fig. 8B



900
902
910
912
914
920
922
924
930
932
934
942
943
944
945
945
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947
948
950
952
953
954
955
957
960
V_1
V_2
V_3

Fig. 9

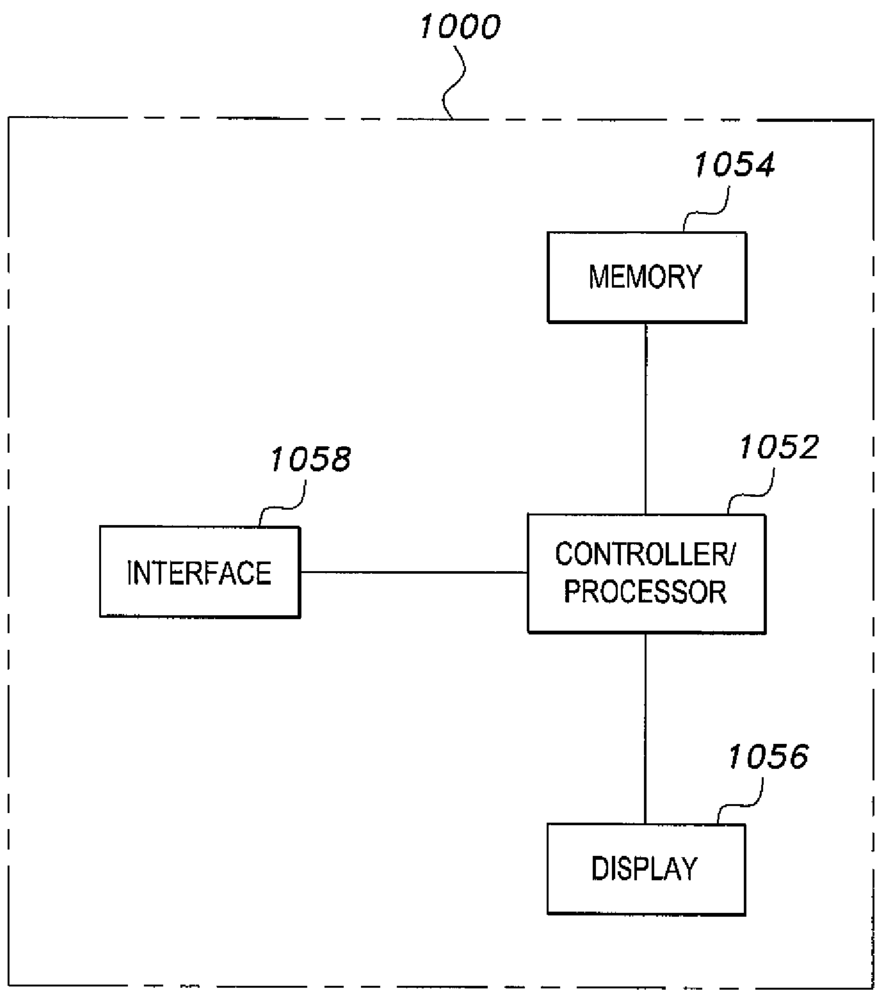

1000
1054
MEMORY
1058
1052
INTERFACE
CONTROLLER/
PROCESSOR
1056
DISPLAY

Fig. 10

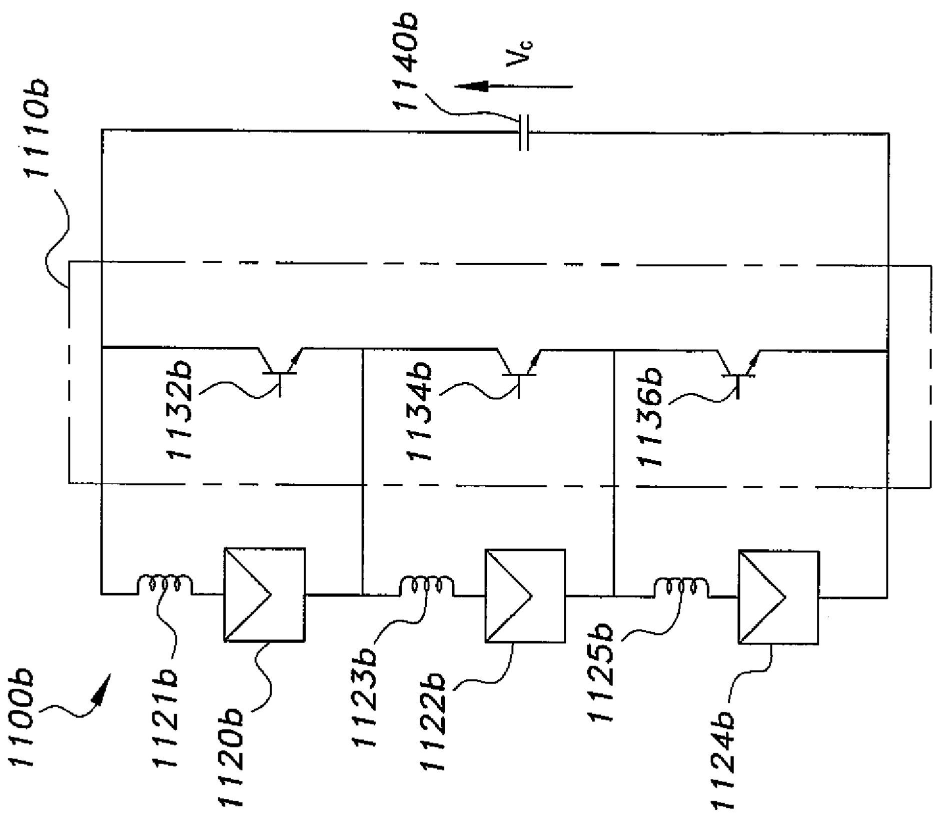


Fig. 11B

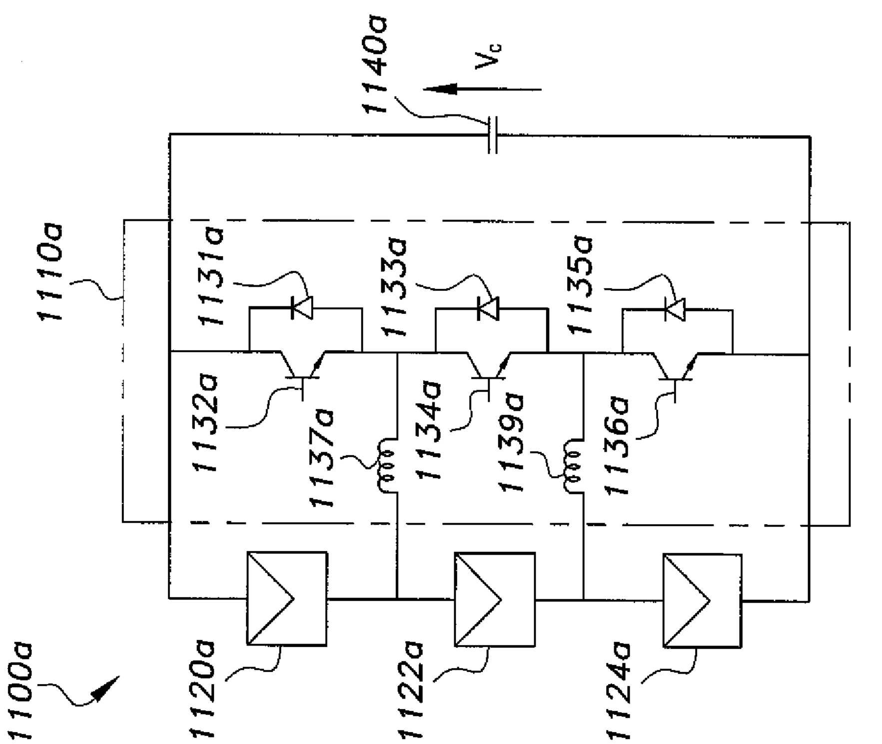


Fig. 11A

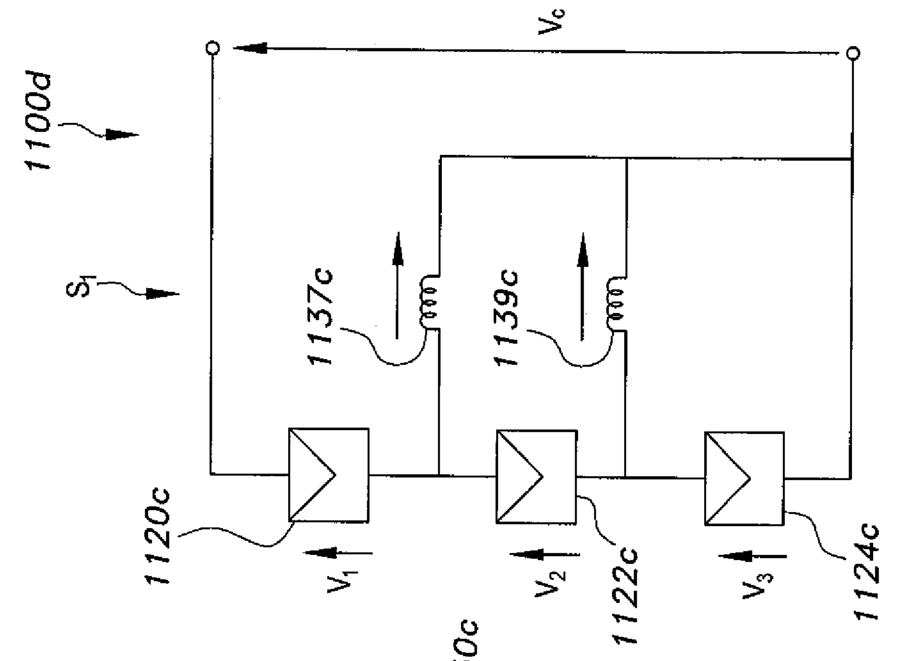


Fig. 11D

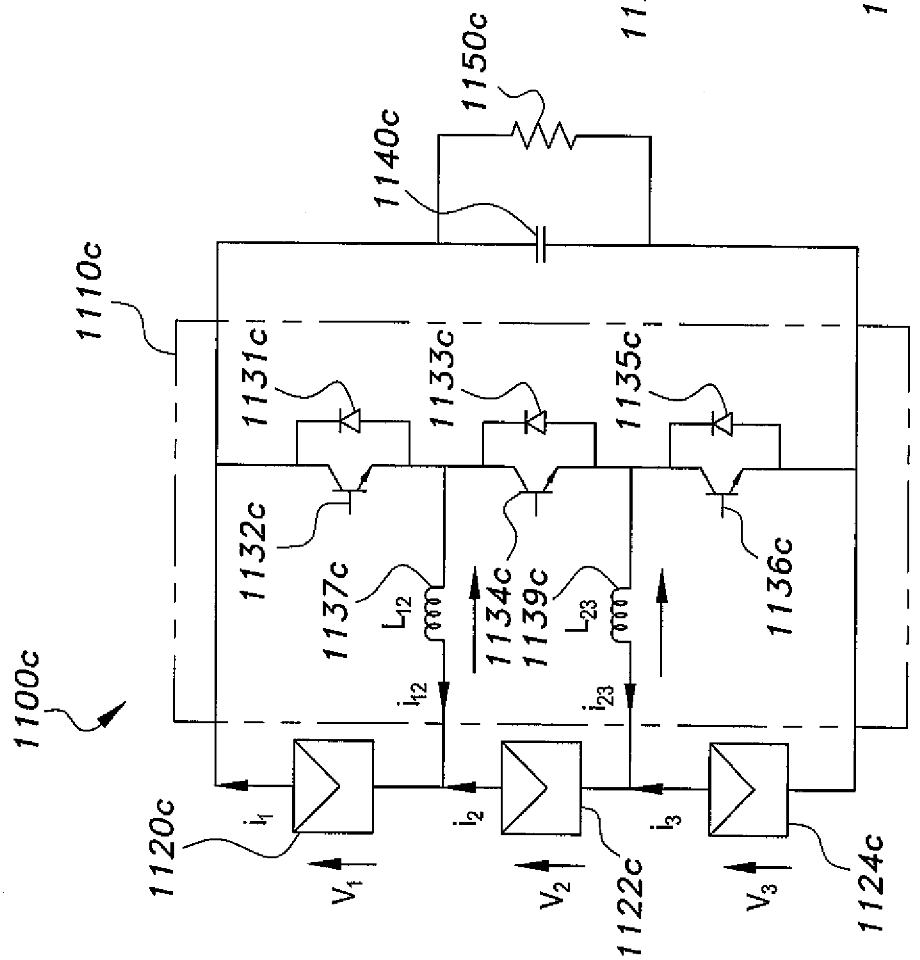


Fig. 11C

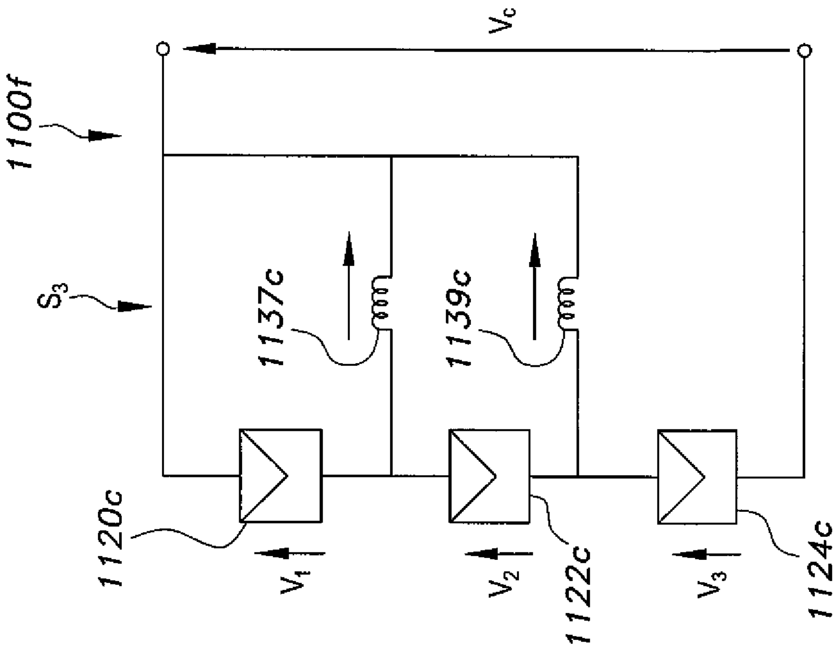


Fig. 11F

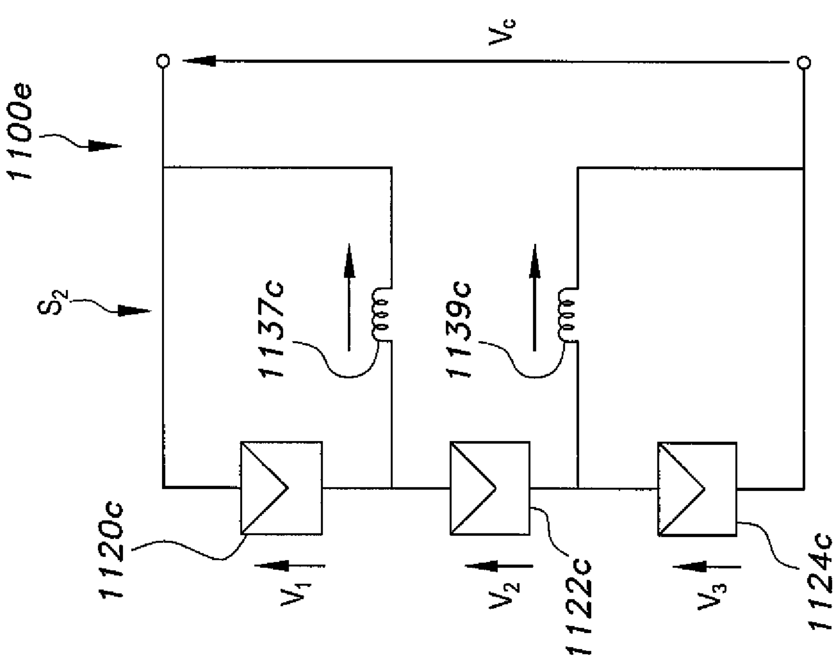
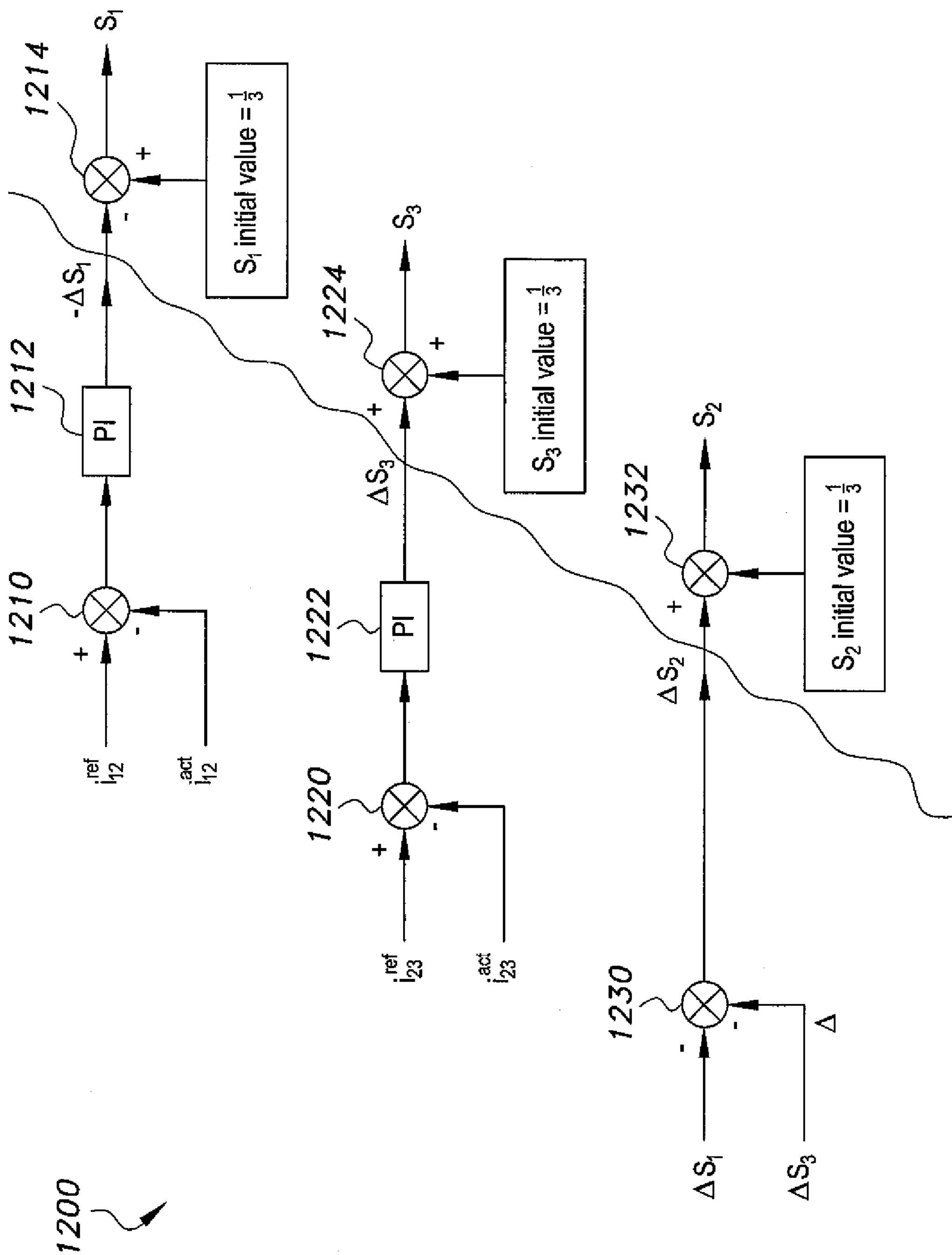


Fig. 11E



1200
1210
1212
PI
1214
$-\Delta S_1$
S_1
S_1 initial value = $\frac{1}{3}$
i_{12}^{ref}
i_{12}^{act}
1220
1222
PI
1224
ΔS_3
S_3
S_3 initial value = $\frac{1}{3}$
i_{23}^{ref}
i_{23}^{act}
1230
1232
ΔS_2
S_2
S_2 initial value = $\frac{1}{3}$
ΔS_1
ΔS_3
Δ

Fig. 12

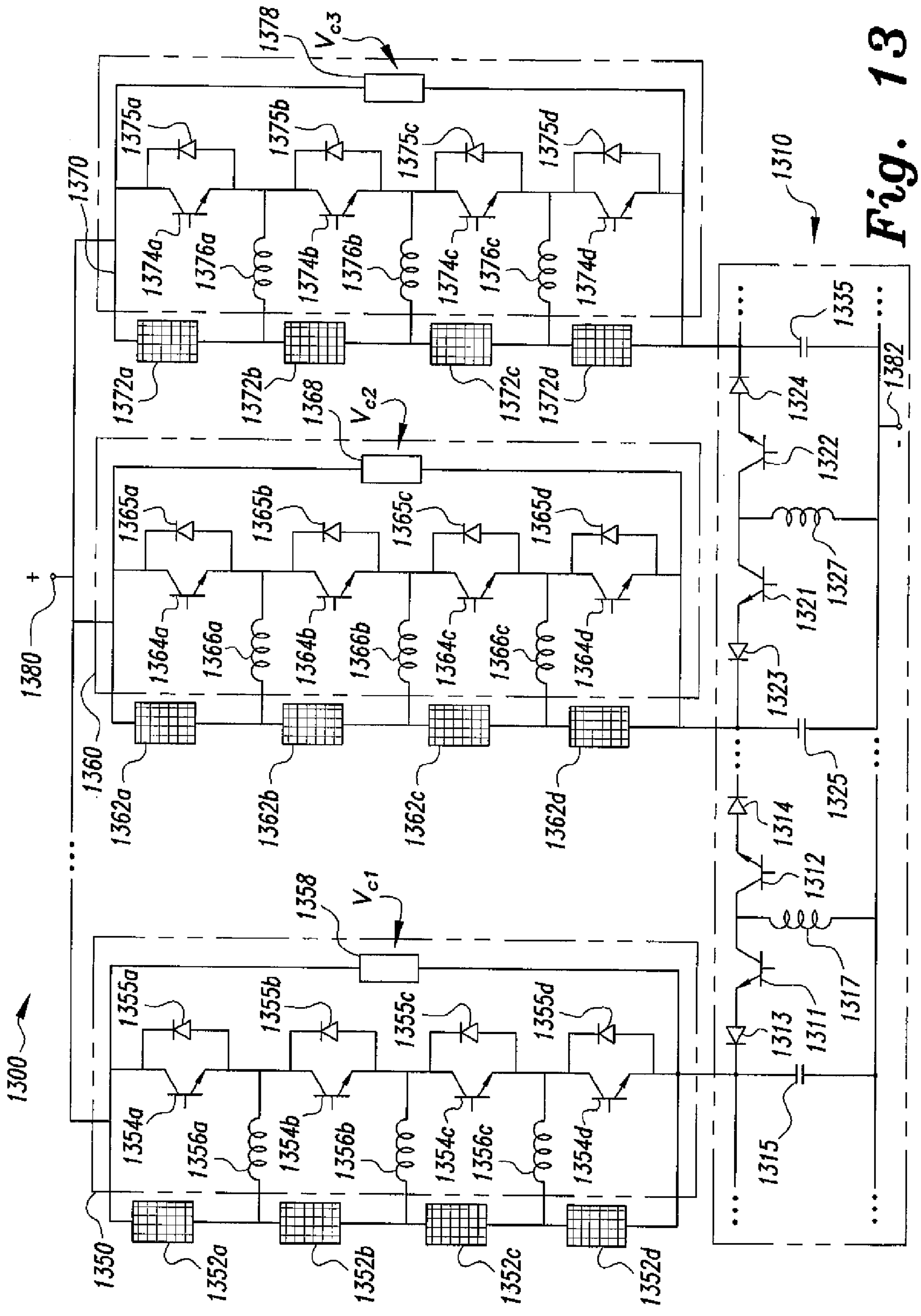

1300
1350
1352a
1352b
1352c
1352d
1354a
1354b
1354c
1354d
1355a
1355b
1355c
1355d
1356a
1356b
1356c
1356d
1358
V_{c1}
1360
1362a
1362b
1362c
1362d
1364a
1364b
1364c
1364d
1365a
1365b
1365c
1365d
1366a
1366b
1366c
1368
V_{c2}
1370
1372a
1372b
1372c
1372d
1374a
1374b
1374c
1374d
1375a
1375b
1375c
1375d
1376a
1376b
1376c
1378
V_{c3}
1380
+
1382
-
1310
1311
1312
1313
1314
1315
1317
1321
1322
1323
1324
1325
1327
1335

Fig. 13

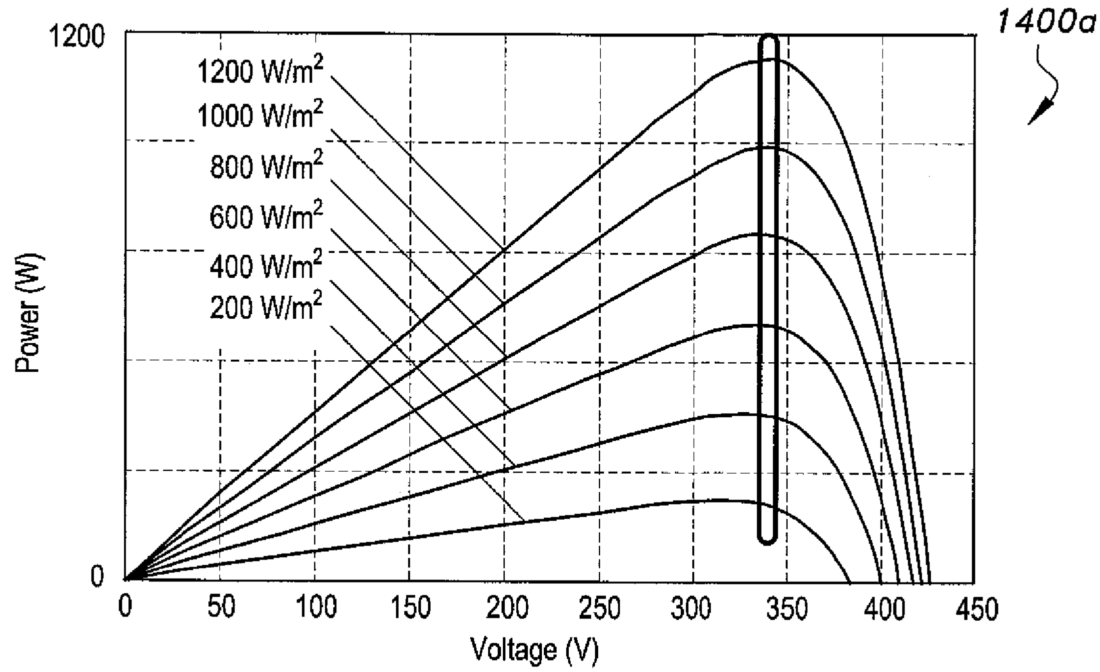


Fig. 14A

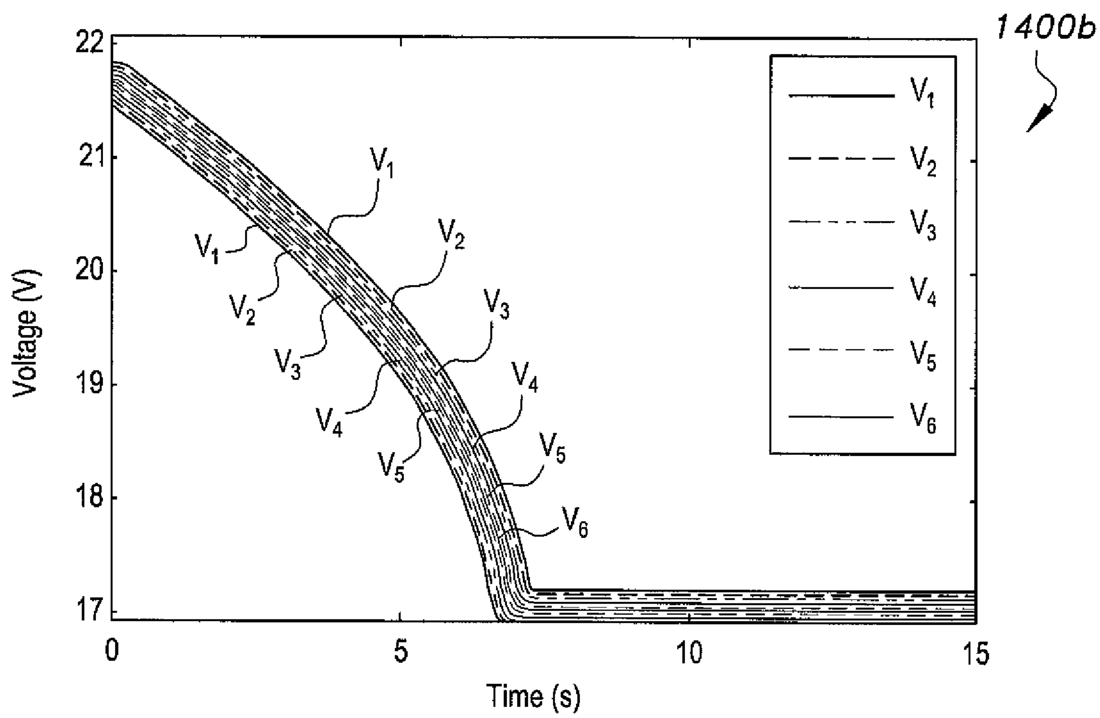


Fig. 14B

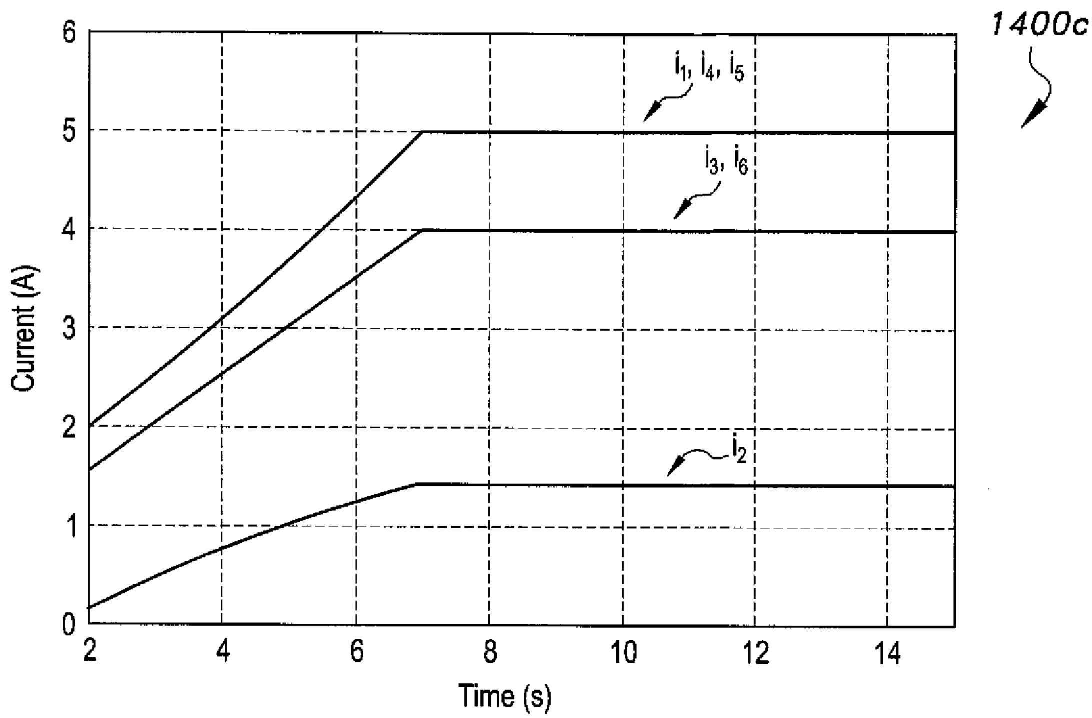


Fig. 14C

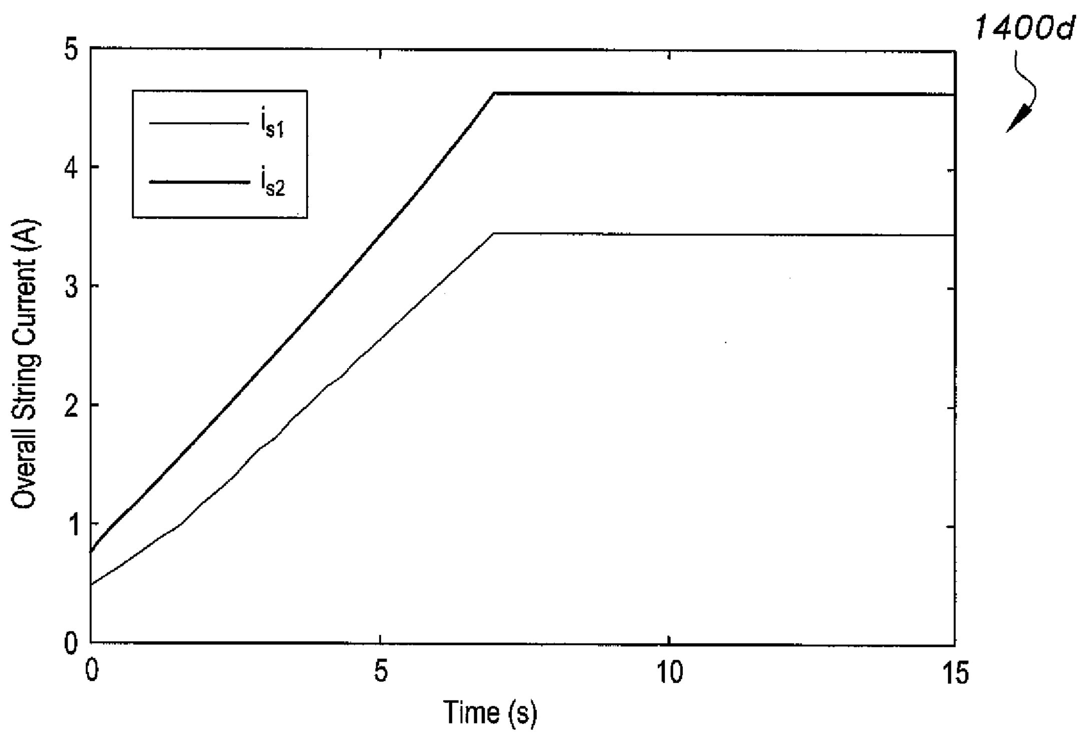


Fig. 14D

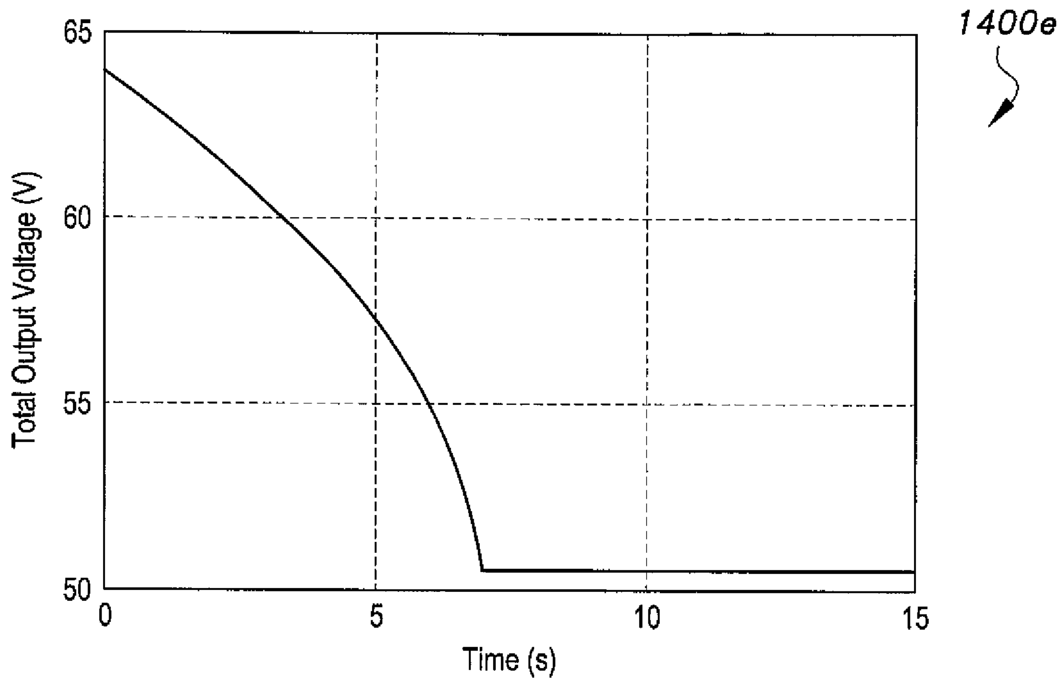


Fig. 14E

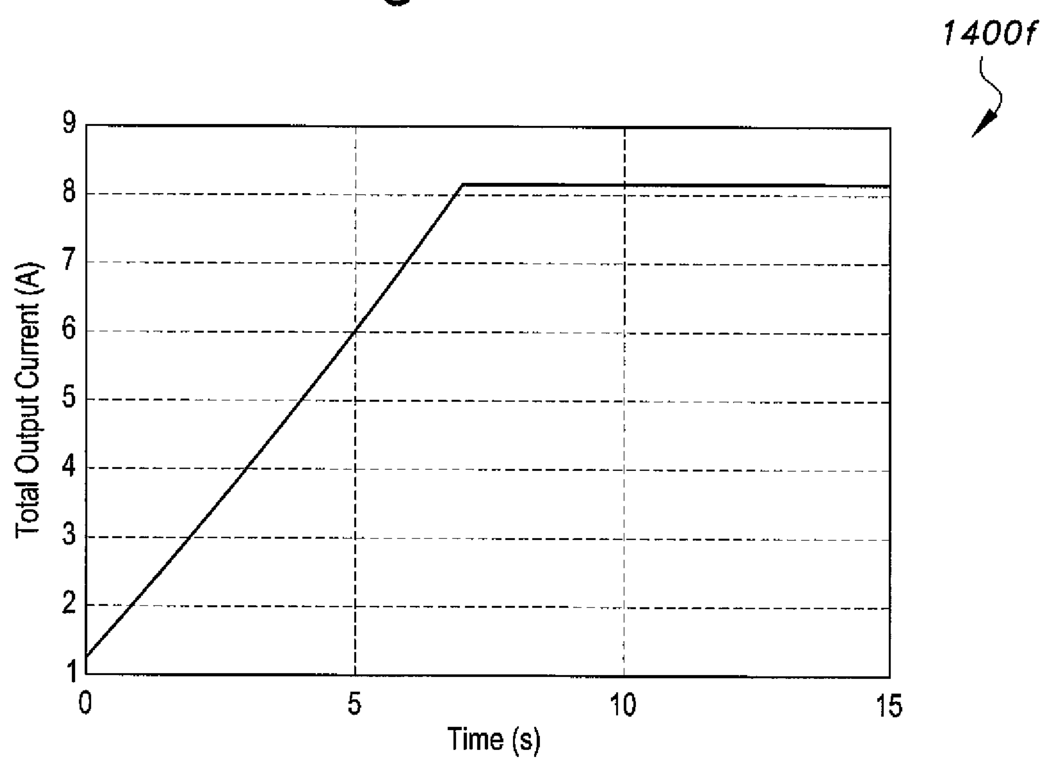


Fig. 14F

1400g

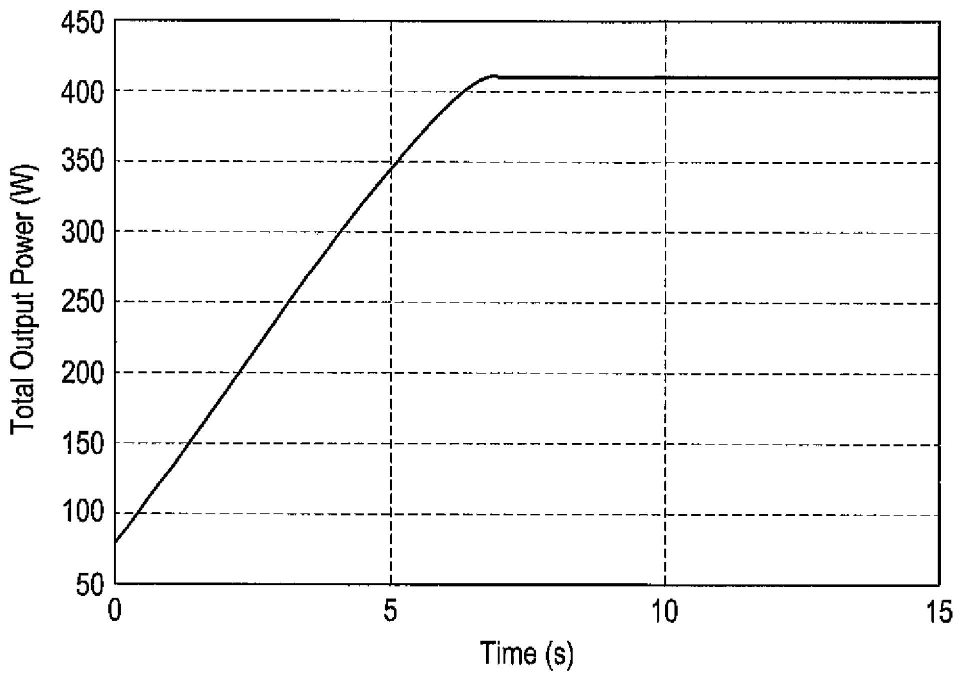


Fig. 14G

APPARATUS AND METHOD FOR VOLTAGE AND CURRENT BALANCING IN GENERATION OF OUTPUT POWER IN POWER GENERATION SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of priority under 35 USC §119 to U.S. Provisional Patent Application No. 61/860,567, filed Jul. 31, 2013 in the United States Patent Office, incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to electrical systems, and particularly to voltage and current balancing of generated output power in power generation electrical systems, such as for solar or wind power generation.

2. Description of the Related Art

Alternative energy generation serves as an alternative to traditional use of fossil fuel to generate electricity. Forms of alternative energy include solar energy, wind energy, geothermal energy, biofuel, hydrogen, and the like. Alternative energy generation has certain advantages over fossil fuels, such as being ecologically friendly. In the recent years, there has been increased interest and investment into alternative energy generation. However, alternative energy generation can be inefficient and costly when compared to the use of fossil fuel. Accordingly, it is desirable to provide improved systems and methods for alternative energy generation.

In such systems for alternative energy generation, one approach is to connect strings of direct current (DC) voltage sources in parallel to increase power throughput, such as the case in photovoltaic (PV) arrays, series connected DC output wind farms, batteries, and capacitors, and it is desirable to maintain the voltage of the parallel strings at an equal value. Strings of DC voltage sources can be placed in parallel before being connected to a central inverter to increase throughput. In such configuration, it is desirable to have the same string voltage for the DC voltage source strings in order to prevent any current circulation. In some embodiments, a series diode can be used with every string in order to prevent current circulation. When a string's voltage differs from the rest of the parallel strings, that string is "taken out" or excluded from the parallel combination, thus, typically reducing the total output power. In cases of PV arrays, this can occur because one or more PV modules in the DC voltage source string are shaded, covered with debris or snow, aging or aged, defective, non-homogenous (e.g., produced by different manufacturers), and the like, for example.

In recently years, such as over the past 5-7 years, for example, microinverters have been introduced and are becoming relatively widespread. One of the first commercial products for microinverters was that developed by Enphase Energy in 2008. Since then, a relatively small number of companies have developed microinverter concepts and are commercializing or in the process of commercializing such concepts.

However, in some cases, microinverter systems can have certain drawbacks especially when utility scale installations are in question. In such systems, high voltages typically are required in order to assist in preventing power losses in the system wiring. Strings of series connected microinverters can likely provide an advantage. However, in some cases, synchronization and control of these strings of AC inverters is not trivial, and typically are not necessarily very practical. However, in certain applications, using DC microinverters can provide advantages in power generation, for example.

In this regard, a relatively detailed evaluation of wind farm layouts using both AC and DC components is described in S. Lundberg, "Evaluation of wind farm layouts," EPE Journal, vol. 19, no. 1, pp. 157-169 (March 2004), the entirety of which in incorporated by reference herein as part of this specification. The criterion of investigation is the energy production cost. If renewable energy systems based on wind power production are to become widespread, this criterion generally needs to be evaluated in light of new developments in power generation technology. The energy production cost used in the article is defined as the total investment cost divided by the total energy production of a wind farm. To determine the energy production and the investment cost, accurate loss and cost models are typically desirable, for example.

In certain cases, modern offshore wind farms use AC transmission. Such systems typically utilize an offshore transformer station to raise the voltage from the wind turbines, for example, to 132-150 kV for transmission to shore, for example. Many of the wind farm topologies studied in the above Lundberg EPE Journal article have such an offshore platform. However, offshore platforms are typically complex and costly. In order to reduce complexity and cost, parallel strings of series connected DC output wind turbines can be utilized, as for example, the power generation system **300***b* illustrated in FIG. **3**B.

In this regard, for example, FIG. **1**C illustrates an example of a power generation system having line-commutated converters (LCCs) with a static synchronous compensator (STATCOM) for high voltage direct current (HVDC) transmission. FIG. **1**C illustrates a power generation system **100***c* that is a classical LCC based system with a STATCOM. The power generation system **100***c* includes a plurality of DC voltage sources, such as the wind turbines **110***c* and **115***c*, which provide a DC voltage power to the HVDC converter that includes a smoothing reactor, filters F and a point of common coupling (PCC) from which a converted AC voltage is provided to an electrical grid.

Classical LCC based HVDC transmission systems, such as of the type of the power generation system **100***c*, are based on current source converters with naturally commutated thyristors, so called line-commutated converters (LCC). However, such systems typically only can transfer power between two active AC networks. Thus they typically are less useful in connection with wind farms as the offshore AC grid typically needs to be powered up prior to a possible startup. Also, such classical LCC HVDC systems, such as the power system **100** generally cannot provide independent control of the active and reactive powers, as well as can produce relatively large amounts of harmonics can makes the use of large filters inevitable.

One feasible solution, for the grid connection of offshore wind farms, is so-called "hybrid HVDC" transmission which generally combines a line commutated converter with a STATCOM, as illustrated in the power generation system **100***c*. The STATCOM can provide the necessary commutation voltage to the HVDC converter and the reactive power compensation to the network during steady state, dynamic and transient conditions. Also, it can provide limited active power support to the offshore network during transient conditions, for example. Also, the LCC can be relatively reliable with relatively little maintenance. Further compared to voltage source converter (VSC) based power generation schemes, such as illustrated in FIG. **1**D, LCC based HVDC transmission, such as illustrated in the power generation system **100***c* of FIG. **100***c*, typically has much lower power losses (i.e. only 2-3 converter losses) and for high ratings it has comparably relatively low capital costs. However, based on overall system economics, LCC based HVDC transmission typically only merits consideration for transmission capacities above approximately 600 megawatts (MW).

Also, as to VSC based power generation systems, FIG. **1**D illustrates an example of a voltage source converter (VSC) based power generation system for high voltage direct current (HVDC) transmission. FIG. **1**D illustrates a power generation system **100***d* that is a VSC based system. The power generation system **110***c* includes a plurality of DC voltage sources, such as the wind turbines **110***d* and **115***d*, which provide a DC voltage power to the HVDC converter that includes a phase reactor, filters F and a point of common coupling (PCC) from which the converted AC voltage is provided to an electrical grid.

VSC based HVDC power generation and transmission type systems have been around since their first commercial installation in 1999, such as in providing generated power to a grid connection from relatively large offshore wind farms, for example. With a VSC type power generation system there is typically no need for an active commutation voltage. Therefore, VSC based HVDC transmission typically does not require a relatively strong offshore or onshore AC network and can even start up against a dead network (black-start capability). In VSC based power generation systems, the active and reactive power can be controlled independently, which can reduce a need for reactive power compensation and can contribute to stabilize the AC network at their connection points.

Also, in VSC based power generation systems, such as in the power generation system **100***d*, use of insulated-gate bipolar transistor (IGBT) semiconductors can allow for much higher switching frequencies which can reduce the harmonic content of the VSC based systems. Therefore, the filter requirements on the AC side of VSC based power generation systems can be significantly reduced compared to conventional HVDC converters, for example. However, the high-frequency pulse-width modulation (PWM) switching can result in comparatively high converter losses.

While a total efficiency of the two converter stations of a VSC based HVDC transmission system can be less than that of an LCC based system, the cost of VSC based systems is still relatively high due to the more advanced semiconductor valves generally required. In this regard, in order to handle the high voltage, multiple IGBTs typically have to be connected in series, which likely makes the valves expensive, as complex gate drives and voltage sharing circuitries are generally required. Also, VSC based HVDC transmission systems are typically relatively competitive at transmission distances over 100 km or power levels of between approximately 200 MW and 900 MW.

FIG. **1**E illustrates a graph **100***e* of transmission capacity in megawatts (MW) versus transmission distance in kilometers (km) for various HVAC and LCC/VSC based HVDC power generation systems, HVAC transmission systems have been used for the vast a majority of offshore wind farms commissioned to date, which currently can cover distances up to 100 kilometers (km) and power transmission capacities up to 200 MW, for example. For larger and more remote wind farms, transmission losses are can increase relatively significantly due to capacitive charging currents, which can limit the use of HVAC transmission systems, such as illustrated in and according to the graph **100***e* of FIG. **1**E, for example.

Such use of parallel strings of series connected DC output wind turbines can provide a relatively low energy cost and the required high voltage generally can be obtained without use of a central DC-DC converter. Another advantage of the topology can be that turbine voltage insulation stresses are relatively reduced, and can be handled by the transformer in the local DC-DC converter. However, as described in S. Lundberg, "Wind farm configuration and energy efficiency studies—series DC versus AC layouts," PhD Thesis, Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden (ISSN-0346-718X 2006), the entirety of which is incorporated by reference herein as part of this specification, individual wind turbine converters typically need to be designed (or overrated) for a voltage level of about 35% above the nominal voltage.

Such design for an overrated voltage level typically is due to the fact that if one turbine does not feed out energy and therefore fails to hold output voltage, other turbines must compensate for this by increasing their output voltage. While overrating all the wind turbine converters of a wind farm can provide a solution to extend the operation of the wind farm during turbine outages, this can be a relatively costly alternative that can have limitations, such as especially in relatively larger power generation systems.

Accordingly, it is desirable to provide improved systems and methods for alternative energy generation for power generation systems, such as to increase the efficiency of power generation in a cost effective manner.

Thus, string voltage balancing converters, and voltage and current balancing circuitry and topologies in the generation of output power in power generation systems, addressing the aforementioned problems is desired.

SUMMARY OF THE INVENTION

Embodiments of string voltage balancing power converters, as can include embodiments of voltage balancing circuits and topologies, as can be combined with embodiments of current balancing circuits and topologies, as described herein, of various configurations for power generation electrical systems are provided to balance series DC source or series strings of DC sources that are placed in parallel. Embodiments of string voltage balancing power converters for power generation electrical systems can be advantageously used in photovoltaic (PV) arrays and plants, wind farms based on the series/parallel connection of DC output turbine converters, battery banks, capacitor banks, and the like, for example.

Embodiments of apparatuses and methods for voltage balancing parallel arranged DC voltage source strings in a power generation system includes a string voltage balancing circuit having reverse blocking switches to control a current flow and an output voltage of the DC voltage source strings. Capacitors are connected to a corresponding reverse blocking switch and in series with a corresponding one of the plurality of DC voltage source strings to construct a voltage difference for a corresponding one of the plurality DC voltage source strings. The string voltage balancing circuit adjusts an output voltage of the DC voltage source strings by controlling a current flowing in the plurality of DC voltage source strings to adjust a voltage constructed across corresponding ones of the capacitors to balance the output voltage for the DC voltage source strings to be substantially the same output voltage.

Embodiments of apparatuses and methods for current balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system include a differential power processing (DPP) current balancing circuit. The DPP current balancing circuit includes a plurality of reverse blocking switches connected to a plurality of series connected DC voltage source modules forming corresponding ones of the plurality of DC voltage source strings to control currents respectively flowing through each of the series connected DC voltage source modules. A plurality of inductors connected to the series connected DC voltage source modules and to the plurality of reverse blocking switches induce a corresponding voltage based on the flow of the respective controlled currents to balance a current between corresponding ones of the series connected DC voltage source modules to adjust the respective currents flowing through each of the plurality of series connected DC voltage source modules.

These and other features of the present invention will become readily apparent upon further review of the following specification and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates general schematic diagram of a power generation system with DC voltage sources connected in parallel utilizing a central inverter that changes a DC voltage to an AC voltage to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **1**B illustrates a general schematic diagram of a power generation system with DC voltage source strings connected in parallel, which utilizes a central inverter that changes a DC voltage to an AC voltage according to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **1**C illustrates an example of a power generation system having line-commutated converters (LCCs) with a static synchronous compensator (STATCOM) for high voltage direct current (HVDC) transmission to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **1**D illustrates an example of a voltage source converter (VSC) based power generation system for high voltage direct current (HVDC) transmission to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **1**E illustrates a graph of transmission capacity in megawatts (MW) versus transmission distance in kilometers (km) for various HVAC and LCC/VSC based HVDC power generation systems.

FIG. **2**A illustrates a power generation system with DC voltage sources connected in parallel, which utilizes multiple inverters that change a DC voltage to an AC voltage to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **2**B illustrates a power generation system with DC voltage source strings connected in parallel, which utilizes multiple inverters that change a DC voltage to an AC voltage to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **3**A illustrates a power generation system with DC voltage sources connected in parallel that utilizes microinverters that change a DC voltage to an AC voltage to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **3**B illustrates a power generation system with DC voltage source strings connected in parallel that utilizes DC microinverters and a central inverter that change a DC voltage to an AC voltage to which embodiments of DC voltage balancing circuits and topologies according to the present invention can be applied.

FIG. **4**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit according to the present invention.

FIG. **4**B illustrates a general schematic diagram of an embodiment of a power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit according to the present invention.

FIG. **4**C, FIG. **4**D and FIG. **4**E illustrate graphs of simulation results respectively comparing voltage, current and capacitor voltage, versus time, for the embodiment of a DC voltage balancing circuit of FIG. **4**B according to the present invention.

FIG. **5**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a closed ring balancing converter configuration according to the present invention.

FIG. **5**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a closed ring balancing converter configuration according to the present invention.

FIG. **6**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a complementary terminal balancing converter configuration according to the present invention.

FIG. **6**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a complementary terminal balancing converter configuration according to the present invention.

FIG. **7**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a single star balancing converter configuration according to the present invention.

FIG. **7**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a single star balancing converter configuration according to the present invention.

FIG. **7**C, FIG. **7**D and FIG. **7**E illustrate graphs of simulation results respectively comparing load voltage, DC source current and capacitor voltage, versus time, for the embodiment of a DC voltage balancing circuit of FIG. **7**B according to the present invention.

FIG. **8**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a double star balancing converter configuration according to the present invention.

FIG. **8**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a double star balancing converter configuration according to the present invention.

FIG. **9** illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in an open ring balancing converter configuration according to the present invention.

FIG. **10** is a block diagram of a generalized system, including a controller/processor, a memory, an interface and a display, as can be included in as a control system or controller in implementing control of voltage balancing and current balancing of DC voltage source strings in power generation systems including embodiments of voltage balancing circuits and topologies, as can include or be combined with current balancing circuits and topologies, according to the present invention.

FIG. **11**A illustrates a general schematic diagram of an embodiment of current balancing circuit as can be used in a power generation system of a plurality of DC voltage source strings to balance the current between series connected DC voltage sources, such as PV arrays in a DC voltage source string according to the present invention.

FIG. **11**B illustrates a general schematic diagram of another embodiment of current balancing circuit as can be used in a power generation system of a plurality of DC voltage source strings to balance the current between series connected DC voltage sources, such as PV arrays in a DC voltage source string according to the present invention.

FIG. **11**C illustrates a general schematic diagram of an embodiment of the current balancing circuit of FIG. **11**A to illustrate switching states of switches of the current balancing circuit for differential power processing and difference currents as can be used in a power generation system of a plurality of DC voltage source strings to balance the current between series connected DC voltage sources, such as PV arrays in a DC voltage source string, according to the present invention.

FIG. **11**D illustrates a general schematic diagram of a first switching state (S_1) in an embodiment of the current balancing circuit of FIG. **11**C to balance the current between series connected DC voltage sources, such as PV arrays in a DC voltage source string according to the present invention.

FIG. **11**E illustrates a general schematic diagram of a second switching state (S_2) in an embodiment of the current balancing circuit of FIG. **11**C to balance the current between series connected DC voltage sources, such as PV arrays in a DC voltage source string according to the present invention.

FIG. **11**F illustrates a general schematic diagram of a third switching state (S_3) in an embodiment of the current balancing circuit of FIG. **11**C to balance the current between series connected DC voltage sources, such as PV arrays in a DC voltage source string according to the present invention.

FIG. **12** illustrates a general schematic diagram of an embodiment of a controller illustrating a process for implementing the switching states S_1, S_2 and S_3 of the current balancing circuit of FIG. **11**C for differential power processing as can be used in a power generation system to balance the current between series connected DC voltage sources, such as PV arrays, in a DC voltage source string according to the present invention.

FIG. **13** illustrates a general schematic diagram of an embodiment of a voltage and current balancing circuit topology including a plurality of current balancing circuits for differential power processing to balance the current between series connected DC voltage source modules, such as PV arrays, in a corresponding DC voltage source string integrated with an embodiment of a voltage balancing circuit topology to balance the voltage of a plurality DC voltage source strings in a power generation system according to the present invention.

FIG. **14**A illustrates a graph of power versus time for PV panel characteristics at different insolation levels for differential power processing in current balancing series connected DC voltage sources according to the present invention.

FIG. **14**B, FIG. **14**C, FIG. **14**D, FIG. **14**E, FIG. **14**F and FIG. **14**G illustrate graphs of simulation results respectively comparing voltage, current, overall string current, total output voltage, total output current and total output power, versus time, for a two DC voltage source string current balancing circuit topology, similar to the current balancing topology of FIG. **11**C, as implemented for each DC voltage source string for differential power processing to balance the current between series connected DC voltage source modules, such as PV arrays, in a corresponding DC voltage source string according to the present invention.

Unless otherwise indicated, similar reference characters denote corresponding features consistently throughout the attached drawings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of string voltage balancing power converters, as can include embodiments of voltage balancing circuits and topologies, as can be combined with embodiments of current balancing circuits and topologies, as described herein, of various configurations for power generation electrical systems are provided to balance series DC source or series strings of DC sources that are placed in parallel. Embodiments of string voltage balancing power converters for power generation electrical systems can be advantageously used in photovoltaic (PV) arrays and plants, wind farms based on the series/parallel connection of DC output turbine converters, battery banks, capacitor banks, and the like, for example. In some embodiments of string voltage balancing power converters for power generation electrical systems, string voltage balancing converters balance the voltage on series strings of DC sources that are placed in parallel to maximize power throughput from the system. As discussed herein, such balancing of the voltage on series strings of DC sources can be achieved by controlling the voltage and/or current, such as in embodiments that include placing of a capacitor in series with each DC voltage source string or as can be shared by multiple strings, for example.

FIG. **1**A illustrates general schematic diagram of a power generation system with DC voltage sources connected in parallel utilizing a central inverter that changes a DC voltage to an alternating current (AC) voltage to which embodiments of voltage balancing and current balancing circuits and topologies can be applied. For example, FIG. **1**A illustrates a power generation system **100***a* with DC voltage sources **110***a* connected in parallel, which utilizes a central inverter **120***a* to change a DC voltage to an AC voltage, for example. As is illustrated in FIG. **1**A, DC voltage sources **110***a*, such as can be PV modules, are connected to the central inverter **120***a* which, among other things, converts a DC voltage generated by the DC voltage sources **110***a* to an AC voltage suitable for being supplied to an electrical grid **130***a*. However, one or more DC voltage source strings can be taken out when the generated DC voltage differs from that generated by the rest of DC voltage sources in the power generation system, such as power generation system **100***a*.

FIG. **1**B illustrates a general schematic diagram of a power generation system with DC power generation source strings connected in parallel, which utilizes a central inverter that changes a DC voltage to an AC voltage to which embodiments of voltage balancing and current balancing circuits and topologies can be applied. FIG. **1**B illustrates a power generation system **100***b* with a plurality of DC voltage source strings **140***b* connected in parallel, which utilizes a central inverter **120***b* to convert a DC voltage to an AC voltage, for example. The power generation system **100***b* utilizes a plurality of DC voltage source strings, in which more than one DC voltage source **110***b* make up a corresponding DC voltage source string **140***b*, in place of individual DC voltage sources illustrated in the power generation system **100***a* of FIG. **1**A.

The central converter or central inverter architecture shown in FIGS. **1**A and **1**B in the power generation systems **100***a* and **100***b* can be used in rooftop PV systems (mainly a DC voltage source single string), as well as can be used in relatively large PV plants. In some embodiments of such power generation systems, especially when a proper shading analysis is carried out, the PV system can be designed to operate with several string inverters instead of a central inverter, such as the power generation systems illustrated in FIGS. **2**A and **2**B.

FIG. **2**A illustrates a power generation system with DC voltage sources connected in parallel, which utilizes multiple inverters that change a DC voltage to an AC voltage to which embodiments of voltage balancing and current balancing circuits and topologies can be applied. FIG. **2**A illustrates a power generation system **200***a* with DC sources **210***a* connected in parallel, which utilizes multiple inverters **220***a*, such as a corresponding inverter **220***a* for each DC voltage source **210***a*, for example. Among other things, the inverters **220***a* convert a DC voltage generated by the respective DC voltage sources **210***a* into an AC voltage, which is fed into an electrical grid **230***a*.

FIG. **2**B illustrates a power generation system with DC voltage source strings connected in parallel, which utilizes multiple inverters that change a DC voltage to an AC voltage to which embodiments of voltage balancing and current balancing circuits and topologies can be applied. FIG. **2**B illustrates a power generation system **200***b* with strings of sources **240***b* connected in parallel, which utilizes multiple inverters **220**B according to some embodiments. Power generation system **200***b* utilizes strings of DC sources, in which more than one DC source **110** make up a sources string **240***b*, in place of individual sources illustrated in FIG. **2**A. In some embodiments, more than one string **240***b* can share an inverter **220***b*. In some embodiments, using multiple string inverters (as is shown in FIGS. **2**A and **2**B) adds cost but improves energy harvesting.

Also, FIG. **3**A illustrates a power generation system with DC voltage sources connected in parallel that utilizes microinverters that change a DC voltage to an AC voltage to which embodiments of voltage balancing and current balancing circuits and topologies can be applied. FIG. **3**A illustrates a power generation system **300***a* that utilizes microinverters **305***a* respectively associated with a corresponding DC voltage source **310***a*, for example. The microinverters **305***a* can, among other things, convert a DC voltage into an AC voltage.

Although a microinverter solution concept seems to addresses problems of shading, aging, manufacturer differences, module failures, etc., in power generation systems, use of such microinverters typically is at the expense of placing a power converter inside every module, such as inside or associated with each of the DC voltage sources **310***a*. Also, multiple modules can share the same microinverter, such as a microinverter **305***a*. When microinverters are used, all modules typically can deliver their full potential when placed in parallel.

FIG. **3**B illustrates a power generation system with DC voltage source strings connected in parallel that utilizes DC microinverters and a central inverter that changes a DC voltage to an AC voltage to which embodiments of voltage balancing and current balancing circuits and topologies can be applied. FIG. **3**B illustrates a power generation system **300***b* that utilizes DC microinverters **350***b*, for example. As is illustrated in FIG. **3**B, DC voltage sources **310***b* make up DC voltage source strings **340***b*, which are respectively connected to the microinverters **350***b*. A DC voltage from the microinverters **350***b* is fed to a central inverter **320***b*, which converts the DC voltage into an AC voltage suitable for being fed into the electrical grid **330***b*.

In some embodiments, more than DC voltage source string **340***b* can share the same DC microinverter **350***b*. In some cases, if increased power throughput is required, more DC voltage source strings, such as DC voltage source strings **340***b*, need to be connected in parallel, and a need for voltage balancing of the Dc voltage source string generated voltages emerges, such as to enhance the efficiency of the power generation system.

In electrical power generation systems, such as those described above with respect to FIGS. **1**A-**3**B, control of power generation to balance series DC source or series strings of DC sources that are placed in parallel can be efficiently enhanced by embodiments of string voltage balancing power converters that include or are associated with embodiments of voltage balancing circuitry and topologies that can also be combined with embodiments of current balancing circuitry and topologies, such as to balance currents flowing in individual modules, such as PV arrays, of a corresponding DC voltage source string, for power generation, such as those illustrated in the embodiments FIGS. **4-9** and **11**A-**11**F and in embodiments of a combined voltage balancing and current balancing circuit and topology, such as illustrated in FIG. **13**.

Embodiments of string voltage balancing converters including voltage balancing and/or current balancing circuits and topologies, as described herein, can address, among other things, overrating requirements of DC source converters, such as wind turbine converters in a series connected to a DC wind farm. Also, embodiments of string voltage balancing converters including embodiments of voltage balancing circuits and topologies, as well as can also include embodiments of current balancing circuits and topologies, can be configured into architectures to balance any number of a plurality of DC voltage source strings, such as DC voltage source strings of PV panels or of DC output turbines, for example, as can depend on the use of application, and should not be construed in a limiting sense.

Referring now to FIG. **4**A, a general schematic diagram is illustrated of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit. FIG. **4**A illustrates a power generation system **400***a* that includes a string voltage balancing circuit **410***a*. The power generation system **400***a* includes two unbalanced strings of DC voltage sources **402***a* and **404***a*, such as of PV panels or wind turbines, connected in parallel. For example, for purposes of illustration, the DC voltage source string **402***a* can generate a 100 kV output voltage V_1 and the DC voltage source string **404***a* can generate an 80 kV output voltage V_2. The DC voltage source strings **402***a* and **404***a* are connected to a load **430***a* to which an output voltage is provided.

The string voltage balancing circuit **410***a* is connected between DC voltage source strings **402***a* and **404***a*. The string voltage balancing circuit **410***a* includes two reverse blocking switches (e.g., valves) **422***a* and **426***a*, an inductor **416***a*, and two capacitors **412***a* and **414***a*. The inductor **416***a* is connected between the switches **422***a* and **426***a* and the switches **422***a* and **426***a* divide the inductor **416***a* current between the two lines, such as according to their operating operation point, for example. The switches **422***a* and **426***a* can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense. In some embodiments, the switches **422***a* and **426***a* have reverse blocking capability or, as illustrated, can be connected to series diodes **424***a* and **428***a* configured to block reverse current to provide a reverse blocking capability, for example.

In the power generation system **400***a* of FIG. **4**A, the voltage unbalance between the lines connected to the DC voltage sources strings **402***a* and **404***a* is translated into a negative potential on one capacitor (e.g., capacitor **412***a* connected to the higher line voltage side) and positive potential on the other capacitor (e.g., capacitor **414***a* connected to the lower line voltage side). The capacitors **412***a* and **414***a*, respectively, pull down and pull up the voltage on the lines connected to the DC voltage source strings **402***a* and **404***a* so that the voltage is balanced or substantially balanced across the parallel DC voltage source lines **402***a* and **404***a* (e.g., to 75 kV).

FIG. **4**B illustrates a general schematic diagram of an embodiment of a power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit. Similar to the power generation system **400***a* of FIG. **4**A, FIG. **4**B illustrates a power generations system **400***b* that includes a string voltage balancing circuit **410***b*. The power generation system **400***b* includes two unbalanced strings of DC voltage sources **402***b* and **404***b*, such as of PV panels or wind turbines, connected in parallel. For example, for purposes of illustration, the DC voltage source string **402***b* can generate a 100 kV output voltage V_I and the DC voltage source string **404***b* can generate an 80 kV output voltage V_2. The DC voltage source strings **402***b* and **404***b* are connected to a load **430***b* to which an output voltage is provided.

The string voltage balancing circuit **410***b* is connected between the DC voltage source strings **402***b* and **404***b*. The string voltage balancing circuit **410***b* includes two IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **422***b* and **426***b*, an inductor **416***b*, and two capacitors **412***b* and **414***b*. Use of IGBT type switches for the switches **422***b* and **426***b* can allow for relatively higher switching frequencies and can reduce harmonic content, for example. The inductor **416***b* is connected between the switches **422***b* and **424***b*, and the switches **422***b* and **426***b* divide the inductor **416***b* current between the two lines, such as according to their operating operation point, for example. The power generation system **400***b* also includes an inductor **440***b* in series with the capacitor **412***b* and the DC voltage source string **402***b* and an inductor **442***b* in series with the capacitor **414***b* and the DC voltage source string **404***b*. The inductors **440***b* and **442***b* can act as a filter, such as to minimize or reducing a ripple current, for example.

The switches **422***b* and **426***b*, in addition to being IGBT type semiconductor switches, can also include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense. In some embodiments, the switches **422***b* and **426***b* can have reverse blocking capability or, as illustrated, can be connected to series diodes **424***b* and **428***b* configured to block reverse current to provide a reverse blocking capability, for example.

Operation and processes for embodiments of string voltage balancing circuits topologies, such as for the string voltage balancing circuits **410***a* and **401***b*, can also be extended and applied to other embodiments of voltage balancing circuit topologies, such as those illustrated in FIGS. **5**A-**9**, for example.

In the embodiments of the operation and process, the string voltage balancing circuits **410***a* and **410***b* are respectively connected between the two DC voltage source strings, such as the two unbalanced DC voltage source strings **402***a* and **404***a* and the two unbalanced DC voltage source strings **402***b* and **404***b* of the power generation systems **400***a* and **400***b*, respectively, providing output voltages of V_1 and V_2. The string voltage balancing circuits **410***a* and **410***b* respectively include two reverse blocking switches, the switches **422***a* and **426***a* respectively in conjunction with diodes **424***a* and **428***a* and the switches **422***b* and **426***b* respectively in conjunction with diodes **424***b* and **428***b*, and respectively include the inductors **416***a* and **416***b* and the capacitors **412***a*, **414***a*, **412***b* and **414***b*. The switches **422***a* and **426***a* of the voltage balancing circuits **410***a* and the switches **422***b* and **426***b* of the voltage balancing circuit **410***b* are turned on alternately, such that the duty ratio or duty cycle of first switch **422***a*, **422***b* (δ_1) plus the duty ratio or duty cycle of second switch **426***b*, **426***b* (δ_2) is equal or substantially equal to one, $\delta_1+\delta_2=1$, for example.

The duty ratio or duty cycle of the first switch **422***a*, **422***b* (δ_1) and the duty ratio or duty cycle of the second switch **426***a*, **426***b* (δ_2) are controlled to get the desired output DC voltage across the load terminals of the power generation system. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by a generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense. The voltage unbalance in the lines is translated into a negative potential on one capacitor (higher line voltage side), and positive potential on the other capacitor (lower line voltage side) to provide the voltage balancing, for example.

Also, operation and processes for embodiments of string voltage balancing circuits topologies, such as for the string voltage balancing circuits **410***a* and **410**, can also be extended and applied to other embodiments of voltage balancing circuit topologies, such as those illustrated in FIGS. **5**A-**9**, for example.

FIG. **10** is a block diagram of a generalized system, including a controller/processor, a memory, an interface and a display, as can be included in as a control system or controller in implementing control of voltage balancing and current balancing of DC voltage source strings in power generation systems including embodiments of voltage balancing circuits and topologies, as can include or be combined with current balancing circuits and topologies, such as in the voltage balancing and current balancing circuits and topologies of FIGS. **4**A-**9** and FIGS. **11**A-**13**.

Referring now to FIG. **10**, there is illustrated a block diagram of a generalized system **1000**, including a controller/processor **1052**, a memory **1054** a display **1056** and an interface **1058**, as can be used for implementing operations and control of voltage balancing circuits and topologies and current balancing circuits and topologies for string voltage balancing converters for power generation electrical systems. It should be understood that the generalized system **1000** can represent, for example, a stand-alone computer, computer terminal, portable computing device, networked computer or computer terminal, networked portable device, programmable logic controller (PLC) or an application specific integrated circuit (ASIC). The generalized system **1000**, or portions thereof, can be incorporated in or implemented as components of a control simulator system, or other suitable control system, for operation and control of embodiments of string voltage balancing converters, such as for voltage balancing, as can be combined with current balancing, for DC voltage source strings in electrical power generation systems, such as those described and illustrated herein, for example.

Data, programs, instructions or control operations can be entered into the generalized system **1000** by the user or can be received by the generalized system **1000** via any suitable type of user or other suitable interface **1058**, and can be stored in a computer readable memory **1054**, which can be any suitable type of computer readable and programmable memory. Calculations or operations, such as in the control and operation of the string voltage balancing converters for power generation electrical systems, such as described herein, are performed by the controller/processor **1052**, which can be any suitable type of computer processor, programmable logic controller (PLC) or ASIC, for example. Information and data, such as messages, settings or results of the control operation for voltage and current balancing, for example, can be displayed to the user on a display **1056**, which can be any suitable type of computer display or digital display, for example, such as a liquid crystal display (LCD).

The controller/processor **1052** can be associated with, or incorporated into, any suitable type of computing device, for example, a personal computer, a PLC or ASIC. The display **1056**, the controller/processor **1052**, the memory **1054**, and any associated computer readable media are in communication with one another by any suitable type of data bus, as is well known in the art.

Examples of computer readable media include a magnetic recording apparatus, non-transitory computer readable storage memory, an optical disk, a magneto-optical disk, and/or a semiconductor memory (for example, RAM, ROM, etc.). Examples of magnetic recording apparatus that can be used in addition to the memory **1054**, or in place of the memory **1054**, include a hard disk device (HDD), a flexible disk (FD), and a magnetic tape (MT). Examples of the optical disk include a DVD (Digital Versatile Disc), a DVD-RAM, a CD-ROM (Compact Disc-Read Only Memory), and a CD-R (Recordable)/RW.

The generalized system **1000** of FIG. **10** can be used as a generalized control simulator system to consider and evaluate various string voltage balancing converters on energy production cost or in relation to dynamic evaluation of string voltage balancing converters, such as when utilized in conjunction with various power generation electrical systems, as used with PV arrays, a series connected DC wind turbine farm or a multilayered wind farm model, for example.

Further, the generalized system **1000** can be used in simulation of operation and control and in operation and control of string voltage balancing converters for power generation electrical systems, such as can implement control of voltage balancing and current balancing in embodiments of string voltage balance converters. An example of the generalized system **1000**, such as for a generalized control simulator system, can be a TAMUQ real time simulator, such as can be based on the Opal-RT real time environment, for example, as can implement control the voltages, currents and switch operation in the various embodiments of string voltage balancing converters for power generation electrical systems, such as described herein.

A generalized control simulator system, such as can be implemented by the generalized system **1000** can include a RT Lab processing unit, such as includes a controller/processor and memory to store instructions and programs to implement the string voltage balance converter control. The generalized control simulator system can also include a user console monitor to control the string voltage balancing and current balancing, as can also display the control operations and results of the string voltage balancing converter control, and can include an analog/digital interface to interface with the power generation system components and string voltage balancing converters, as can be associated with an uninterruptible power supply (UPS) unit to provide power for the power generation system and string voltage balancing converter control operation.

FIG. **4**C, FIG. **4**D and FIG. **4**E illustrate graphs of simulation results respectively comparing voltage, current and capacitor voltage, versus time, for an embodiment of a DC voltage balancing circuit of FIG. **4**B. Referring to FIGS. **4**C-**4**E, the simulation results for an embodiment of the voltage balancing circuit **410*b*** in the power generation system **400*b*** of FIG. **4**B are presented. In the simulation, for the two DC voltage source strings **402*b*** and **404*b*,** the voltage generated by the first DC voltage source string **402*b*** was 100 kilovolts (kV) and the voltage generated by the second DC voltage source string **404*b*** was 80 kV.

Also, in the simulation, the duty ratio or duty cycle of first switch **422*b*** (δ_1) and the duty ratio or duty cycle of second switch **426*b*** (δ_2) each were equal to 50% of the total duty cycle, such that their duty ratios or duty cycles were equal or substantially equal to one, $\delta_1+\delta_2=1$, in the voltage balancing process, such as by simulation control implemented by a computer processor in Matlab®, as can be implemented by the generalized system **1000** of FIG. **10**. The inductance of the inductors **416*b*,** **440*b*** and **442*b*** were each equal to 5 millihenry(ies) (mH) and the capacitance of the capacitors **412*b*** and **414*b*** were each equal to 1 millifarad (mF), a switching frequency of the switches **422*b*** and **426*b*** was 1 kilohertz (kHz) and the load **430*b*** was set to 10 ohms.

FIG. **4**C illustrates a graph **400*c*** of simulation results comparing voltage (kV) versus time (seconds (s)). In the graph **400*c*** it can be seen that the voltage generated by the DC voltage source string **402*b*** was 100 kV, the voltage generated by the second DC voltage source string **404*b*** was 80 kV and the load voltage on the load **430*b*** was 90 kV, indicating a voltage balancing for the DC voltage source strings **402*b*** and **404*b*.**

FIG. **4**D illustrates a graph **400*d*** of simulation results comparing current (amperes (A)) versus time (s). In the graph **400*d*,** it can be seen that the current I_1 for the DC voltage source string **402*b*** and the current I_2 for the DC voltage source string **404*b*,** were substantially balanced with respect to each other.

FIG. **4**E illustrates a graph **400*e*** of simulation results comparing capacitor voltage (kV) versus time (s). In the graph **400*e*,** it can be seen that the voltage for the capacitor **412*b*** is approximately −10 kV of a negative potential on the higher voltage line side of the 100 kV voltage generated by the DC voltage source string **402*b*** of 100 kV and that the voltage for the capacitor **414*b*** is approximately 10 kV of a positive potential on the lower voltage line side of the 80 kV generated by the DC voltage source string **404*b*** for the DC voltage source string **404*b*,** indicating a voltage balancing for the DC voltage source strings **402*b*** and **404*b*.**

Also, the string voltage balancing circuits **410*a*** and **410*b*** respectively illustrated in FIGS. **4**A and **4**B can be generalized an extended to any number of a plurality of DC voltage source strings connected in parallel. It has to be noted that the voltage balancing circuits and topologies as illustrated in FIGS. **4**A and **4**B, and as described herein, can be extended to architectures including n parallel connected DC converters for a corresponding power generation system having a plurality of DC voltage source strings to be balanced, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **5**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC string voltage balancing circuit in a closed ring voltage balancing configuration. FIG. **5**A illustrates an embodiment of a power generation system **500***a* that utilizes a closed ring string voltage balancing circuit **510***a*. The closed ring string voltage balancing circuit **510***a* forms a closed loop ring, such as illustrated in FIG. **5**A.

The power generation system **500***a* includes three unbalanced DC voltage source strings **502***a*, **504***a* and **506***a*, such as of PV panels or wind turbines. For example, for purposes of illustration, the DC voltage source string **502***a* can generate a 100 kV output voltage V_1, the DC voltage source string **504***a* can generate an 80 kV output voltage V_2 and the DC voltage source string **506***a* can generate a 90 kV output voltage V_3. As illustrated, the DC voltage sources strings **502***a*, **504***a*, and **506***a* are connected in parallel. The DC voltage source strings **502***a*, **504***a*, and **506***a* are also connected in parallel to a load **530***a* to which an output voltage is provided.

The closed ring string voltage balancing circuit **510***a* is connected between the DC voltage source strings **502***a*, **504***a* and **506***a*. Also, the closed ring voltage balancing circuit **510***a*, in the embodiment of FIG. **5**A, includes three string voltage balancing circuits **540***a*, **550***a* and **560***a*, similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B, forming the closed loop string voltage balancing circuit **510***a*.

The first string voltage balancing circuit **540***a* balances the voltages generated by the DC voltage source strings **502***a* and **506***a*, the second string voltage balancing circuit **550***a* balances the voltages generated by the DC voltage source strings **502***a* and **504***a* and the third string voltage balancing circuit **560***a* balances the voltages generated by the DC voltage source strings **504***a* and **506***a*, similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B. The closed ring string voltage balancing circuit **510***a* can therefore be considered as an extension of the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B. Also, an embodiment of the closed loop string voltage balancing circuit **510***a* forms the closed loop to include six switches, such as six transistors, as can include various types of transistors, for example. As is illustrated in FIG. **5**A, a string voltage balancing circuit is inserted between any two of the three DC voltage sources strings **502***a*, **504***a*, and **506***a*.

As described, the first string voltage balancing circuit **540***a* is connected between the DC voltage source strings **502***a* and **506***a* to balance the voltages generated by the DC voltage source strings **502***a* and **506***a*. The first string voltage balancing circuit **540***a* includes two reverse blocking switches (e.g., valves) **541***a* and **542***a*, an inductor **545***a* (L_1), and two capacitors **548***a* (C_1) and **568***a* (C_3). The inductor **545***a* (L_1) is connected between the switches **541***a* and **542***a*, and the switches **541***a* and **542***a* divide the inductor **545***a* (L_1) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **541***a* and **542***a* have reverse blocking capability or, as illustrated, can be connected to series diodes **543***a* and **544***a* configured to block reverse current to provide a reverse blocking capability, for example.

As also described, the second string voltage balancing circuit **550***a* is connected between the DC voltage source strings **502***a* and **504***a* to balance the voltages generated by the DC voltage source strings **502***a* and **504***a*. The second string voltage balancing circuit **550***a* includes two reverse blocking switches (e.g., valves) **551***a* and **552***a*, an inductor **555***a* (L_2), and two capacitors **548***a* (C_1) and **558***a* (C_2). The inductor **555***a* (L_2) is connected between the switches **551***a* and **552***a*, and the switches **551***a* and **552***a* divide the inductor **555***a* (L_2) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **551***a* and **552***a* have reverse blocking capability or, as illustrated, can be connected to series diodes **553***a* and **554***a* configured to block reverse current to provide a reverse blocking capability, for example.

Also, as described, the third string voltage balancing circuit **560***a* is connected between the DC voltage source strings **504***a* and **506***a* to balance the voltages generated by the DC voltage source strings **504***a* and **506***a*. The third string voltage balancing circuit **560***a* includes two reverse blocking switches (e.g., valves) **561***a* and **562***a*, an inductor **565***a* (L_3), and two capacitors **558***a* (C_2) and **568***a* (C_3). The inductor **565***a* (L_3) is connected between the switches **561***a* and **562***a*, and the switches **561***a* and **562***a* divide the inductor **565***a* (L_3) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **561***a* and **562***a* have reverse blocking capability or, as illustrated, can be connected to series diodes **563***a* and **564***a* configured to block reverse current to provide a reverse blocking capability, for example.

In the string voltage balancing circuits **540***a*, **550***a* and **560***a*, the switches **541***a* and **542***a*, the switches **551***a* and **552***a* and the switches **561***a* and **562***a* can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **5**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC string voltage balancing circuit in a closed ring voltage balancing configuration, similar to the power generation system **500***a* and the closed loop string voltage balancing circuit **510***a*. FIG. **5**B illustrates an embodiment of a power generation system **500***b* that utilizes a closed ring string voltage balancing circuit **510***b*. The closed ring string voltage balancing circuit **510***b* forms a closed loop ring, such as illustrated in FIG. **5**B.

The power generation system **500***b* includes three unbalanced DC voltage source strings **502***b*, **504***b* and **506***b*, such as of PV panels or wind turbines. For example, for purposes of illustration, the DC voltage source string **502***b* can generate a 100 kV output voltage V_1, the DC voltage source string **504***b* can generate an 80 kV output voltage V_2 and the DC voltage source string **506***b* can generate a 90 kV output voltage V_3. As illustrated, the DC voltage sources strings **502***b*, **504***b*, and **506***b* are connected in parallel. The DC voltage source strings **502***b*, **504***b*, and **506***b* are also connected in parallel to a load **530***b* to which an output voltage is provided.

The closed ring string voltage balancing circuit **510***b* is connected between the DC voltage source strings **502***b*, **504***b* and **506***b*. Also, the closed ring voltage balancing circuit **510***b*, in the embodiment of FIG. **5**B, similar to the closed ring string voltage balancing circuit **510***a*, includes three string voltage balancing circuits **540***b*, **550***b* and **560***b*, which are also similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B, forming the closed loop string voltage balancing circuit **510***b*.

The first string voltage balancing circuit **540***b* balances the voltages generated by the DC voltage source strings **502***b* and **506***b*, the second string voltage balancing circuit **550***b* balances the voltages generated by the DC voltage source strings **502***b* and **504***b* and the third string voltage balancing circuit **560***b* balances the voltages generated by the DC voltage source strings **504***b* and **506***b*, similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B. The closed ring string voltage balancing circuit **510***b* can likewise be considered as an extension of the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B. Also, an embodiment of the closed loop string voltage balancing circuit **510***b* forms the closed loop to include six switches, such as six transistors, as can include various types of transistors, for example. As is illustrated in FIG. **5**B, a string voltage balancing circuit is inserted between any two of the three DC voltage sources strings **502***b*, **504***b*, and **506***b*.

As described, the first string voltage balancing circuit **540***b* is connected between the DC voltage source strings **502***b* and **506***b* to balance the voltages generated by the DC voltage source strings **502***b* and **506***b*. The first string voltage balancing circuit **540***b* includes two IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **541***b* and **542***b* (e.g., valves). Use of IGBT type switches for the switches **541***b* and **542***b* can allow for relatively higher switching frequencies and can reduce harmonic content, for example.

The first string voltage balancing circuit **540***b* also includes an inductor **545***b* (L_1), and two capacitors **548***b* (C_1) and **568***b* (C_3). The inductor **545***b* (L_1) is connected between the switches **541***b* and **542***b*, and the switches **541***b* and **542***b* divide the inductor **545***b* (L_1) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **541***b* and **542***b* have reverse blocking capability or, as illustrated, can be connected to series diodes **543***b* and **544***b* configured to block reverse current to provide a reverse blocking capability, for example.

As also described, the second string voltage balancing circuit **550***b* is connected between the DC voltage source strings **502***b* and **504***b* to balance the voltages generated by the DC voltage source strings **502***b* and **504***b*. The second string voltage balancing circuit **550***b* includes two IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **551***b* and **552***b* (e.g., valves). Use of IGBT type switches for the switches **551***b* and **552***b* can allow for relatively higher switching frequencies and can reduce harmonic content, for example.

The second string voltage balancing circuit **550***b* also includes an inductor **555***b* (L_2), and two capacitors **548** (C_1) and **558** (C_2). The inductor **555***b* (L_2) is connected between the switches **551***b* and **552***b*, and the switches **551***b* and **552***b* divide the inductor **555***b* (L_2) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **551***b* and **552***b* have reverse blocking capability or, as illustrated, can be connected to series diodes **553***b* and **554***b* configured to block reverse current to provide a reverse blocking capability, for example.

Also, as described, the third string voltage balancing circuit **560***b* is connected between the DC voltage source strings **504***b* and **506***b* to balance the voltages generated by the DC voltage source strings **504***b* and **506***b*. The third string voltage balancing circuit **560***b* includes two IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **561***b* and **562***b* (e.g., valves). Use of IGBT type switches for the switches **561***b* and **562***b* can allow for relatively higher switching frequencies and can reduce harmonic content, for example.

The third string voltage balancing circuit **560***b* also includes an inductor **565***b* (L_3), and two capacitors **558***b* (C_2) and **568***b* (C_3). The inductor **565***b* (L_3) is connected between the switches **561***b* and **562***b*, and the switches **561***b* and **562***b* divide the inductor **565***b* (L_3) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **561***b* and **562***b* have reverse blocking capability or, as illustrated, can be connected to series diodes **563***b* and **564***b* configured to block reverse current to provide a reverse blocking capability, for example.

In the string voltage balancing circuits **540***b*, **550***b* and **560**, the switches **541***b* and **542***b*, the switches **551***b* and **552***b* and the switches **561***b* and **562***b*, in addition to being IGBT type semiconductor switches, can also include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

Also, as illustrated in FIG. **5**B, the power generation system **500***b* also includes an inductor **507***b* in series with the capacitor **548***b* and the DC voltage source string **502***b*, an inductor **508***b* in series with the capacitor **558***b* and the DC voltage source string **504***b* and an inductor **509***b* in series with the capacitor **568***b* and the DC voltage source string **506***b*. The inductors **507***b*, **508***b*, and **509***b* can act as a filter, such as to minimize or reducing a ripple current, for example, in the power generation system **500***b*.

The duty ratios or duty cycles, δ_1-δ_6, of the corresponding switches **541***a*, **542***a*, **551***a*, **552***a*, **561***a* and **562***a* in the closed loop string voltage balancing circuit **510***a* and of the corresponding switches **541***b*, **542***b*, **551***b*, **552***b*, **561***b* and **562***b* in the closed loop string voltage balancing circuit **510***b* are controlled to get the desired output DC voltage across the load terminals, such as the loads **530***a* and **530***b* of the power generation system. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense. The voltage unbalance in the lines can be translated into a negative potential on a corresponding capacitor, a positive potential on a corresponding capacitor or a zero potential on a corresponding capacitor to provide the voltage balancing, for example.

The closed loop string voltage balancing circuits **510***a* and **510***b* respectively illustrated in FIGS. **5**A and **5**B can be generalized an extended to any number of a plurality of DC voltage source strings connected in parallel. It is noted that the voltage balancing circuits and topologies as illustrated in FIGS. **5**A and **5**B, and as described herein, can be extended to architectures including n parallel connected DC converters for a corresponding power generation system having a plurality of DC voltage source strings to be balanced, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **6**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a complementary terminal balancing converter configuration. FIG. **6**A illustrates an embodiment of a power generation system **600***a* that utilizes a complimentary string voltage balancing circuit **601***a*. The complimentary string voltage balancing circuit **601***a* includes two string voltage balancing circuits **610***a* and **620***a* that together form the complimentary string voltage balancing circuit **601***a*, such as illustrated in FIG. **6**A.

The power generation system **600***a* includes three unbalanced DC voltage source strings **602***a*, **604***a* and **606***a*, such as of PV panels or wind turbines. As illustrated, the DC voltage sources strings **602***a*, **604***a*, and **606***a* are connected in parallel. The DC voltage source strings **602***a*, **604***a*, and **606***a* are also connected in parallel to a load **630***a* to which an output voltage is provided.

The first and second string voltage balancing circuits **610***a* and **620***a* of the complimentary string voltage balancing circuit **601***a* are respectively connected between the DC voltage source strings **602***a*, **604***a* and **606***a*. Also, the first and second string voltage balancing circuits **610***a* and **620***a* of the complimentary string voltage balancing circuit **601***a* are each similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B, forming the complimentary string voltage balancing circuit **601***a*.

The first string voltage balancing circuit **610***a* balances the voltages generated by the DC voltage source strings **602***a* and **604***a*, and the second string voltage balancing circuit **620***a* balances the voltages generated by the DC voltage source strings **604***a* and **606***a*, similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B. The complimentary string voltage balancing circuit **601***a* can therefore be considered as an extension of the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B.

As described, the first string voltage balancing circuit **610***a* is connected between the DC voltage source strings **602***a* and **604***a* to balance the voltages generated by the DC voltage source strings **602***a* and **604***a*. The first string voltage balancing circuit **610***a* includes two reverse blocking switches (e.g., valves) **611***a* and **612***a*, an inductor **615***a* (L_1), and two capacitors **616***a* (C_1) and **617***a* (C_2). The inductor **615***a* (L_1) is connected between the switches **611***a* and **612***a*, and the switches **611***a* and **612***a* divide the inductor **615***a* (L_1) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **611***a* and **612***a* have reverse blocking capability or, as illustrated, can be connected to series diodes **613***a* and **614***a* configured to block reverse current to provide a reverse blocking capability, for example.

As also described, the second string voltage balancing circuit **620***a* is connected between the DC voltage source strings **604***a* and **606***a* to balance the voltages generated by the DC voltage source strings **604***a* and **606***a*. The second string voltage balancing circuit **620***a* includes two reverse blocking switches (e.g., valves) **621***a* and **622***a*, an inductor **625***a* (L_2), and two capacitors **626***a* (C_3) and **627***a* (C_4). The inductor **625***a* (L_2) is connected between the switches **621***a* and **622***a*, and the switches **621***a* and **622***a* divide the inductor **625***a* (L_2) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **621***a* and **622***a* have reverse blocking capability or, as illustrated, can be connected to series diodes **623***a* and **624***a* configured to block reverse current to provide a reverse blocking capability, for example.

In the first and second string voltage balancing circuits **610***a* and **620***a*, the switches **611***a* and **612***a* and the switches **621***a* and **622***a* can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

As is illustrated in the power generation system **600***a*, the first string voltage balancing circuit **610***a* is connected between the DC voltage source strings **602***a* and **604***a*, and the second string voltage balancing circuit **620***a* is connected between the DC voltage source strings **604***a* and **606***a*, with the capacitance of the middle line, i.e., the DC voltage source string **604***a*, being split between the capacitor **617***a* (C_2) of the first string voltage balancing circuit **610***a* and the capacitor **626***a* (C_3) of the second string voltage balancing circuit **620***a*, for example. The complimentary string voltage balancing circuit **601***a* including the first and second string voltage balancing circuits **610***a* and **620***a* can minimize the number of components for voltage balancing compared to the closed ring string voltage balancing circuit **510***a* illustrated in FIG. **5**A, for example.

For example, for purposes of illustration, the DC voltage source string **602***a* can generate a 100 kV output voltage V_1, the DC voltage source string **604***a* can generate an 80 kV output voltage V_2 and the DC voltage source string **606***a* can generate a 90 kV output voltage V_3. Therefore, the first and second string voltage balancing circuits **610***a* and **620***a* of the complementary string voltage balancing circuit **601***a* can balance or substantially balance the DC voltage source strings **602***a*, **604***a* and **606***a* output voltage at 90 kV, for example.

In such case, the voltage across the capacitor **616***a* (C_1) is −10 kV, the voltage across the capacitor and **617***a* (C_2) is 10 kV, the voltage across the capacitor **626***a* (C_3) is 0 kV and the voltage across the capacitor and **627***a* (C_4) is 0 kV, for example. A possible drawback of the complimentary string voltage balancing circuit **601***a* including the first and second string voltage balancing circuits **610***a* and **620***a* illustrated in FIG. **6**A is that the first and second string voltage balancing circuits **610***a* and **620***a* are respectively located at opposite ends of the DC voltage source strings **602***a*, **604***a* and **606***a*, for example.

FIG. **6**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a complementary terminal balancing converter configuration. FIG. **6**B illustrates an embodiment of a power generation system **600***b* that utilizes a complimentary string voltage balancing circuit **601***b*, similar to the complimentary string voltage balancing circuit **601***a* of FIG. **6**A. The complimentary string voltage balancing circuit **601***b* includes two string voltage balancing circuits **610***b* and **620***b* that together form the complimentary string voltage balancing circuit **601***b*, such as illustrated in FIG. **6**B.

The power generation system **600***b* includes three unbalanced DC voltage source strings **602***b*, **604***b* and **606***b*, such as of PV panels or wind turbines. As illustrated, the DC voltage sources strings **602***b*, **604***b*, and **606***b* are connected in parallel. The DC voltage source strings **602***b*, **604***b*, and **606***b* are also connected in parallel to a load **630***b* to which an output voltage is provided.

The first and second string voltage balancing circuits **610***b* and **620***b* of the complimentary string voltage balancing circuit **601***b* are respectively connected between the DC voltage source strings **602***b*, **604***b* and **606***b*. Also, the first and second string voltage balancing circuits **610***b* and **620***b* of the complimentary string voltage balancing circuit **601***b* are each similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B, forming the complimentary string voltage balancing circuit **601***b*.

The first string voltage balancing circuit **610**b balances the voltages generated by the DC voltage source strings **602**b and **604**b, and the second string voltage balancing circuit **620**b balances the voltages generated by the DC voltage source strings **604**b and **606**b, similar to the string voltage balancing circuits **410**a and **410**b of FIGS. **4**A and **4**B. The complimentary string voltage balancing circuit **601**b can therefore be considered as an extension of the string voltage balancing circuits **410**a and **410**b of FIGS. **4**A and **4**B.

As described, the first string voltage balancing circuit **610**b is connected between the DC voltage source strings **602**b and **604**b to balance the voltages generated by the DC voltage source strings **602**b and **604**b. The first string voltage balancing circuit **610**b includes two IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **611**b and **612**b. Use of IGBT type switches for the switches **611**b and **612**b can allow for relatively higher switching frequencies and can reduce harmonic content, for example.

The first string voltage balancing circuit **610**b includes an inductor **615**b (L_1), and two capacitors **616**b (C_1) and **617**b (C_2). The inductor **615**b (L_1) is connected between the switches **611**b and **612**b, and the switches **611**b and **612**b divide the inductor **615**b (L_1) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **611**b and **612**b have reverse blocking capability or, as illustrated, can be connected to series diodes **613**b and **614**b configured to block reverse current to provide a reverse blocking capability, for example.

As also described, the second string voltage balancing circuit **620**b is connected between the DC voltage source strings **604**b and **606**b to balance the voltages generated by the DC voltage source strings **604**b and **606**b. The second string voltage balancing circuit **620**b includes two IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **621**b and **622**b. Use of IGBT type switches for the switches **621**b and **622**b can allow for relatively higher switching frequencies and can reduce harmonic content, for example.

The second string voltage balancing circuit **620**b also includes an inductor **625**b (L_2), and two capacitors **626**b (C_3) and **627**b (C_4). The inductor **625**b (L_2) is connected between the switches **621**b and **622**b, and the switches **621**b and **622**b divide the inductor **625**b (L_2) current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **621**b and **622**b have reverse blocking capability or, as illustrated, can be connected to series diodes **623**b and **624**b configured to block reverse current to provide a reverse blocking capability, for example.

In the first and second string voltage balancing circuits **610**b and **620**b, the switches **611**b and **612**b and the switches **621**b and **622**b, in addition to being IGBT type semiconductor switches, can also include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

Also, as illustrated in FIG. **6**B, the power generation system **600**b also includes an inductor **607**b in series with the capacitor **616**b and the DC voltage source string **602**b, an inductor **608**b in series with the capacitor **617**b and the DC voltage source string **604**b and an inductor **609**b in series with the capacitor **627**b and the DC voltage source string **606**b. The inductors **607**b, **608**b, and **609**b can act as a filter, such as to minimize or reducing a ripple current, for example, in the power generation system **600**b.

As is illustrated in the power generation system **600**b, the first string voltage balancing circuit **610**b is connected between the DC voltage source strings **602**b and **604**b, and the second string voltage balancing circuit **620**b is connected between the DC voltage source strings **604**b and **606**b, with the capacitance of the middle line, i.e., the DC voltage source string **604**b, being split between the capacitor **617**b (C_2) of the first string voltage balancing circuit **610**b and the capacitor **626**b (C_3) of the second string voltage balancing circuit **620**b, for example. The complimentary string voltage balancing circuit **601**b including the first and second string voltage balancing circuits **610**b and **620**b can minimize the number of components for voltage balancing compared to the closed ring string voltage balancing circuit **510**b illustrated in FIG. **5**B, for example.

For example, for purposes of illustration, the DC voltage source string **602**b can generate a 100 kV output voltage V_1, the DC voltage source string **604**b can generate an 80 kV output voltage V_2 and the DC voltage source string **606**b can generate a 90 kV output voltage V_3. Therefore, the first and second string voltage balancing circuits **610**b and **620**b of the complementary string voltage balancing circuit **601**b can balance or substantially balance the DC voltage source strings **602**b, **604**b and **606**b output voltage at 90 kV, for example.

In such case, the voltage across the capacitor **616**b (C_1) is −10 kV, the voltage across the capacitor and **617**b (C_2) is 10 kV, the voltage across the capacitor **626**b (C_3) is 0 kV and the voltage across the capacitor and **627**b (C_4) is 0 kV, for example. A possible drawback of the complimentary string voltage balancing circuit **601**b including the first and second string voltage balancing circuits **610**b and **620**b illustrated in FIG. **6**B is that the first and second string voltage balancing circuits **610**b and **620**b are respectively located at opposite ends of the DC voltage source strings **602**b, **604**b and **606**b, for example.

The duty ratios or duty cycles, δ_1-δ_4, of the corresponding switches **611**a, **612**a, **621**a and **622**a in the complementary string voltage balancing circuit **601**a and of the corresponding switches **611**b, **612**b, **621**b and **622**b in the complementary string voltage balancing circuit **601**b are controlled to get the desired output DC voltage across the load terminals, such as the loads **630**a and **630**b of the power generation system. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense. The voltage unbalance in the lines can be translated into a negative potential on a corresponding capacitor, a positive potential on a corresponding capacitor or a zero potential on a corresponding capacitor to provide the voltage balancing, for example.

The complementary string voltage balancing circuits **601**a and **601**b respectively illustrated in FIGS. **6**A and **6**B can be generalized an extended to any number of a plurality of DC voltage source strings connected in parallel. It is noted that the voltage balancing circuits and topologies as illustrated in FIGS. **6**A and **6**B, and as described herein, can be extended to architectures including n parallel connected DC converters for a corresponding power generation system having a plurality of DC voltage source strings to be balanced, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **7**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a single star balancing converter configuration. FIG. **7**A illustrates an embodiment of a power generation system **700***a* that utilizes a single star string voltage balancing circuit **710***a*.

The power generation system **700***a* includes three unbalanced DC voltage source strings **702***a*, **704***a* and **706***a*, such as of PV panels or wind turbines. As illustrated, the DC voltage sources strings **702***a*, **704***a*, and **706***a* are connected in parallel. The DC voltage source strings **702***a*, **704***a*, and **706***a* are also connected in parallel to a load **730***a* to which an output voltage is provided.

The single star string voltage balancing circuit **710***a* is respectively connected to the DC voltage source strings **702***a*, **704***a* and **706***a*. Also, the single star string voltage balancing circuit **710***a* is similar in operation to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B, for example. The single star string voltage balancing circuit **710***a* can therefore be considered as an extension of the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B.

The single star string voltage balancing circuit **710***a* is respectively connected to the DC voltage source strings **702***a*, **704***a* and **706***a* to balance the voltages generated by the DC voltage source strings **702***a*, **704***a* and **706***a*. The single star string voltage balancing circuit **710***a* is respectively connected between the DC voltage sources strings **702***a*, **704***a*, and **706***a* and includes one inductor **720***a* (L) and three switches forming a star configuration. Also, the single star string voltage balancing circuit **710***a* can overcome limitations of a relatively large number of components and physical location differences of circuit topology location associated with the closed loop string voltage balancing circuits **510***a* and **510***b* and the complementary string voltage balancing circuits **601***a* and **601***b*, such as illustrated in FIGS. **5**A, **5**B, **6**A and **6**B, respectively, for example.

The single star string voltage balancing circuit **710***a* includes three reverse blocking switches (e.g., valves) **711***a*, **712***a* and **713***a* and includes the inductor **720***a* (L) respectively connected to each of the switches **711***a*, **712***a* and **713***a*. The inductor **720***a* (L) can act to filter out ripples in the individual string currents respectively controlled by the switches **711***a*, **712***a* and **713***a* flowing in the corresponding DC voltage source strings **702***a*, **704***a* and **706***a*.

The single star string voltage balancing circuit **710***a* also includes three capacitors **717***a* (C_1), **718***a* (C_2) and **719***a* (C_3). The capacitor **717***a* (C_1) is connected to the switch **711***a* and is associated with the first DC voltage source string **702***a* to balance the voltage generated by the first DC voltage source string **702***a*. The capacitor **718***a* (C_2) is connected to the switch **712***a* and is associated with the second DC voltage source string **704***a* to balance the voltage generated by the second DC voltage source string **704***a*. The capacitor **719***a* (C_3) is connected to the switch **713***a* and is associated with the third DC voltage source string **706***a* to balance the voltage generated by the third DC voltage source string **706***a*. In some embodiments, the switches **711***a*, **712***a* and **713***a* have reverse blocking capability or, as illustrated, can be connected to series diodes **714***a*, **715***a* and **716***a* configured to block reverse current to provide a reverse blocking capability, for example.

In the single star string voltage balancing circuit **710***a*, the switches **711***a*, **712***a* and **713***a* can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

For example, for purposes of illustration, the first DC voltage source string **702***a* can generate a 100 kV output voltage V_1, the second DC voltage source string **704***a* can generate an 80 kV output voltage V_2 and the third DC voltage source string **706***a* can generate a 90 kV output voltage V_3, Therefore, the single star string voltage balancing circuit **710***a* can balance or substantially balance the DC voltage source strings **702***a*, **704***a* and **706***a* output voltage at 90 kV, for example. In such case, the voltage across the capacitor **717***a* (C_1) is −10 kV, the voltage across the capacitor and **718***a* (C_2) is 10 kV, the voltage across the capacitor **719***a* (C_3) is 0 kV, for example.

FIG. **7**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a single star balancing converter configuration. FIG. **7**B illustrates an embodiment of a power generation system **700***b* that utilizes a single star string voltage balancing circuit **710***b*, similar to the single star string voltage balancing circuit **710***a* of FIG. **7**A.

The power generation system **700***b* includes three unbalanced. DC voltage source strings **702***b*, **704***b* and **706***b*, such as of PV panels or wind turbines. As illustrated, the DC voltage sources strings **702***b*, **704***b*, and **706***b* are connected in parallel. The DC voltage source strings **702***b*, **704**, and **706***b* are also connected in parallel to a load **730***b* to which an output voltage is provided.

The single star string voltage balancing circuit **710***b* is respectively connected to the DC voltage source strings **702***b*, **704***b* and **706***b*. Also, the single star string voltage balancing circuit **710***b* is similar in operation to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B, for example. The single star string voltage balancing circuit **710***b* can therefore be considered as an extension of the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B.

The single star string voltage balancing circuit **710***b* is respectively connected to the DC voltage source strings **702***b*, **704***b* and **706***b* to balance the voltages generated by the DC voltage source strings **702***b*, **704***b* and **706***b*. The single star string voltage balancing circuit **710***b* is respectively connected between the DC voltage sources strings **702***b*, **704***b*, and **706***b* and includes one inductor **720***b* (L) and three switches forming a star configuration. Also, the single star string voltage balancing circuit **710***b* can similarly overcome limitations of a relatively large number of components and physical location differences of circuit topology location associated with the closed loop string voltage balancing circuits **510***a* and **510***b* and the complementary string voltage balancing circuits **601***a* and **601***b*, such as illustrated in FIGS. **5**A, **5**B, **6**A and **6**B, respectively, for example.

The single star string voltage balancing circuit **710***b* includes three IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **711***b*, **712***b* and **713***b*. Use of IGBT type switches for the switches **711***b*, **712***b* and **713***b* can allow for relatively higher switching frequencies and can reduce harmonic content, for example. The single star string voltage balancing circuit **710***b* also includes the inductor **720***b* (L) respectively connected to each the switches **711***b*, **712***b* and **713***b*. The inductor **720***b* (L) can act to filter out ripples in the individual string currents respectively controlled by the switches **711***b*, **712***b* and **713***b* flowing in the corresponding DC voltage source strings **702***b*, **704***b* and **706***b*.

The single star string voltage balancing circuit **710***b* also includes three capacitors **717***b* (C_1), **718***b* (C_2) and **719***b* (C_3). The capacitor **717***b* (C_1) is connected to the switch **711***b* and is associated with the first DC voltage source string **702***b* to balance the voltage generated by the first DC voltage source string **702***b*. The capacitor **718***b* (C_2) is connected to the switch **712***b* and is associated with the second DC voltage source string **704***b* to balance the voltage generated by the second DC voltage source string **704***b*. The capacitor **719***b* (C_3) is connected to the switch **713***b* and is associated with the third DC voltage source string **706***b* to balance the voltage generated by the third DC voltage source string **706***b*. In some embodiments, the switches **711***b*, **712***b* and **713***b* have reverse blocking capability or, as illustrated, can be connected to series diodes **714***b*, **715***b* and **716***b* configured to block reverse current to provide a reverse blocking capability, for example.

In the single star string voltage balancing circuit **710***b*, the switches **711***b*, **712***b* and **713***b*, in addition to being IGBT type semiconductor switches, can also include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

Also, as illustrated in FIG. **7**B, the power generation system **700***b* also includes an inductor **703***b* in series with the capacitor **717***b* (C_1) and the DC voltage source string **702***b*, an inductor **705***b* in series with the capacitor **718***b* (C_2) and the DC voltage source string **704***b* and an inductor **707***b* in series with the capacitor **719***b* (C_3) and the DC voltage source string **706***b*. The inductors **703***b*, **705***b*, and **707***b* can act as a filter, such as to minimize or reducing a ripple current, for example, in the power generation system **700***b*.

For example, for purposes of illustration, the first DC voltage source string **702***b* can generate a 100 kV output voltage V_1, the second DC voltage source string **704***b* can generate an 80 kV output voltage V_2 and the third DC voltage source string **706***b* can generate a 90 kV output voltage V_3. Therefore, the single star string voltage balancing circuit **710***b* can balance or substantially balance the DC voltage source strings **702***b*, **704***b* and **706***b* output voltage at 90 kV, for example. In such case, the voltage across the capacitor **717***b* (C_1) is −10 kV, the voltage across the capacitor and **718***b* (C_2) is 10 kV, the voltage across the capacitor **719***b* (C_3) is 0 kV, for example.

The duty ratios or duty cycles, δ_1-δ_3, of the corresponding switches **711***a*, **712***a*, and **713***a* in the single star string voltage balancing circuit **710***a* and of the corresponding switches **711***b*, **712***b*, and **713***b* in the single star string voltage balancing circuit **710***b* are controlled to get the desired output DC voltage across the load terminals, such as the loads **730***a* and **730***b* of the power generation system. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense. The voltage unbalance in the lines can be translated into a negative potential on a corresponding capacitor, a positive potential on a corresponding capacitor or a zero potential on a corresponding capacitor to provide the voltage balancing, for example.

FIG. **7**C, FIG. **7**D and FIG. **7**E illustrate graphs of simulation results respectively comparing load voltage, DC source current and capacitor voltage, versus time, for an embodiment of the single star string voltage balancing circuit **710***b* of FIG. **7**B. Referring to FIGS. **7**C-**7**E, the simulation results for an embodiment of the single star string voltage balancing circuit **710***b* in the power generation system **700***b* of FIG. **7**B are presented. In the simulation, for the three DC voltage source strings **702***b*, **704***b* and **706***b*, the voltage generated by the first DC voltage source string **702***b* was 100 kilovolts (kV) as V_1, the voltage generated by the second DC voltage source string **704***b* was 80 kV as V_2 and the voltage generated by the third DC voltage source string **706***b* was 90 kilovolts (kV) as V_3.

Also, in the simulation, the duty ratio or duty cycle of first switch **711***b* (δ_1), the duty ratio or duty cycle of second switch **712***b* (δ_2) and the duty ratio or duty cycle of the third switch **713***b* (δ_3) each were equal to 33% of the total duty cycle, such that their duty ratios or duty cycles were equal or substantially equal to one, $\delta_1+\delta_2+\delta_3=1$. The switches **711***b*, **712***b*, and **713***b* were alternately turned on in the voltage balancing process, such as by simulation control implemented by a computer processor in Matlab®, as can be implemented by the generalized system **1000** of FIG. **10**. The inductance of the inductors **703***b*, **705***b*, **707***b* and **720***b* were each equal to 5 millihenry(ies) (mH) and the capacitance of the three capacitors **717***b* (C_1), **718***b* (C_2) and **719***b* (C_3) were each equal to 1 millifarad (mF), a switching frequency of the switches **711***b*, **712***b* and **713***b* was 1 kilohertz (kHz) and the load **730***b* was set to 10 ohms.

FIG. **7**C illustrates a graph **700***c* of simulation results comparing load voltage (kV) versus time (seconds (s)). In the graph **700***c* it can be seen that the load voltage generated by power generation system **700***b* was 90 kV, indicating a voltage balancing for the DC voltage source strings **702***b*, **704***b* and **706***b*.

FIG. **7**D illustrates a graph **700***d* of simulation results comparing DC source current (amperes (A)) versus time (s). In the graph **700***d*, it can be seen that the current I_{sc1} for the first DC voltage source string **702***b*, the current I_{sc2} for the second DC voltage source string **704***b*, and the current I_{sc3} for the third DC voltage source string **706***b* were substantially balanced with respect to each other.

FIG. **7**E illustrates a graph **700***e* of simulation results comparing capacitor voltage (kV) versus time (s). In the graph **700***e*, it can be seen that the voltage V_{c1} for the capacitor **717***b* (C_1) was approximately −10 kV, the voltage V_{c2} for the capacitor **718***b* (C_2) was approximately 10 kV, and the voltage V_{c3} for the capacitor **719***b* (C_3) was approximately 0 kV, indicating a voltage balancing for the DC voltage source strings **702***b*, **704***b* and **706***b*.

The single star string voltage balancing circuits **710***a* and **710***b* respectively illustrated in FIGS. **7**A and **7**B can be generalized an extended to any number of a plurality of DC voltage source strings connected in parallel. It is noted that the voltage balancing circuits and topologies as illustrated in FIGS. **7**A and **7**B, and as described herein, can be extended to architectures including n parallel connected DC converters for a corresponding power generation system having a plurality of DC voltage source strings to be balanced, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **8**A illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a double star balancing converter configuration. FIG. **8**A illustrates an embodiment of a power generation system **800***a* that utilizes a double star string voltage balancing circuit **810***a*.

The power generation system **800***a* includes three unbalanced DC voltage source strings **802***a*, **804***a* and **806***a*, such as of PV panels or wind turbines. As illustrated, the DC voltage sources strings **802**_a_, **804**_a_, and **806**_a_ are connected in parallel. The DC voltage source strings **802**_a_, **804**_a_, and **806**_a_ are also connected in parallel to a load **830**_a_ to which an output voltage is provided.

The double star string voltage balancing circuit **810**_a_ is respectively connected to the DC voltage source strings **802**_a_, **804**_a_ and **806**_a_. Also, the double star string voltage balancing circuit **810**_a_ is similar in operation to the string voltage balancing circuits **410**_a_ and **410**_b_ of FIGS. **4**A and **4**B, for example. The double star string voltage balancing circuit **810**_a_ can therefore be considered as an extension of the string voltage balancing circuits **410**_a_ and **410**_b_ of FIGS. **4**A and **4**B.

The double star string voltage balancing circuit **810**_a_ is respectively connected to the DC voltage source strings **802**_a_, **804**_a_ and **806**_a_, in a generally redundant manner, to balance the voltages generated by the DC voltage source strings **802**_a_, **804**_a_ and **806**_a_. The double star string voltage balancing circuit **810**_a_ is respectively connected between the DC voltage sources strings **802**_a_, **804**_a_, and **806**_a_ and includes two inductors **827**_a_ (L_1) and **837**_a_ (L_2) and six switches forming a double star configuration.

Also, the double star string voltage balancing circuit **810**_a_ can overcome limitations of a relatively large number of components and physical location differences of circuit topology location associated with the closed loop string voltage balancing circuits **510**_a_ and **510**_b_ and the complementary string voltage balancing circuits **601**_a_ and **601**_b_, such as illustrated in FIGS. **5**A, **5**B, **6**A and **6**B, respectively, for example.

A first part of the double star string voltage balancing circuit **810**_a_ includes three reverse blocking switches (e.g., valves) **822**_a_, **824**_a_ and **826**_a_ and includes the inductor **827**_a_ (L_1) respectively connected to each of the switches **822**_a_, **824**_a_ and **826**_a_. The inductor **827**_a_ (L_1) can act to filter out ripples in the individual string currents respectively controlled by the switches **822**_a_, **824**_a_ and **826**_a_ flowing in the corresponding DC voltage source strings **802**_a_, **804**_a_ and **806**_a_.

The first part of the double star string voltage balancing circuit **810**_a_ also includes three capacitors **803**_a_ (C_1), **805**_a_ (C_2) and **807**_a_ (C_3) which are also shared with and included in a second part of the double star string voltage balancing circuit **810**_a_. The capacitor **803**_a_ (C_1) is connected to the switch **822**_a_ and is associated with the first DC voltage source string **802**_a_ to balance the voltage generated by the first DC voltage source string **802**_a_. The capacitor **805**_a_ (C_2) is connected to the switch **824**_a_ and is associated with the second DC voltage source string **804**_a_ to balance the voltage generated by the second DC voltage source string **804**_a_. The capacitor **807**_a_ (C_3) is connected to the switch **826**_a_ and is associated with the third DC voltage source string **806**_a_ to balance the voltage generated by the third DC voltage source string **806**_a_. In some embodiments, the switches **822**_a_, **824**_a_ and **826**_a_ have reverse blocking capability or, as illustrated, can be connected to series diodes **821**_a_, **823**_a_ and **825**_a_ configured to block reverse current to provide a reverse blocking capability, for example.

A second part of the double star string voltage balancing circuit **810**_a_ includes three reverse blocking switches (e.g., valves) **832**_a_, **834**_a_ and **836**_a_ and includes the inductor **837**_a_ (L_2) respectively connected to each the switches **832**_a_, **834**_a_ and **836**_a_. The inductor **837**_a_ (L_2) can act to filter out ripples in the individual string currents respectively controlled by the switches **832**_a_, **834**_a_ and **836**_a_ flowing in the corresponding DC voltage source strings **802**_a_, **804**_a_, and **806**_a_.

Also, the second part of the double star string voltage balancing circuit **810**_a_ also includes the three capacitors **803**_a_ (C_1), **805**_a_ (C_2) and **807**_a_ (C_3), which are also shared with and included in the first part of the double star string voltage balancing circuit **810**_a_. The capacitor **803**_a_ (C_1) is connected to the switch **832**_a_ and is associated with the first DC voltage source string **802**_a_ to balance the voltage generated by the first DC voltage source string **802**_a_. The capacitor **805**_a_ (C_2) is connected to the switch **834**_a_ and is associated with the second DC voltage source string **804**_a_ to balance the voltage generated by the second DC voltage source string **804**_a_. The capacitor **807**_a_ (C_3) is connected to the switch **836**_a_ and is associated with the third DC voltage source string **806**_a_ to balance the voltage generated by the third DC voltage source string **806**_a_. In some embodiments, the switches **832**_a_, **834**_a_ and **836**_a_ have reverse blocking capability or, as illustrated, can be connected to series diodes **831**_a_, **833**_a_ and **835**_a_ configured to block reverse current to provide a reverse blocking capability, for example.

In the double star string voltage balancing circuit **810**_a_, the switches **822**_a_, **824**_a_ and **826**_a_ and the switches **832**_a_, **834**_a_ and **836**_a_ can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

For example, for purposes of illustration, the first DC voltage source string **802**_a_ can generate a 100 kV output voltage, the second DC voltage source string **804**_a_ can generate an 80 kV output voltage and the third DC voltage source string **806**_a_ can generate a 90 kV output voltage. Therefore, the double star string voltage balancing circuit **810**_a_ can balance or substantially balance the DC voltage source strings **802**_a_, **804**_a_ and **806**_a_ output voltage at 90 kV, for example. In such case, the voltage across the capacitor **803**_a_ (C_1) is −10 kV, the voltage across the capacitor and **805**_a_ (C_2) is 10 kV, the voltage across the capacitor **807**_a_ (C_3) is 0 kV, for example.

FIG. **8**B illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in a double star balancing converter configuration. FIG. **8**B illustrates an embodiment of a power generation system **800**_b_ that utilizes a double star string voltage balancing circuit **810**_b_, similar to the double star string voltage balancing circuit **810**_a_.

The power generation system **800**_b_ includes three unbalanced DC voltage source strings **802**_b_, **804**_b_ and **806**_b_, such as of PV panels or wind turbines. As illustrated, the DC voltage sources strings **802**_b_, **804**_b_, and **806**_b_ are connected in parallel. The DC voltage source strings **802**_b_, **804**_b_, and **806**_b_ are also connected in parallel to a load **830**_b_ to which an output voltage is provided.

The double star string voltage balancing circuit **810**_b_ is respectively connected to the DC voltage source strings **802**_b_, **804**_b_ and **806**_b_. Also, the double star string voltage balancing circuit **810**_b_ is similar in operation to the string voltage balancing circuits **410**_a_ and **410**_b_ of FIGS. **4**A and **4**B, for example. The double star string voltage balancing circuit **810**_b_ can therefore be considered as an extension of the string voltage balancing circuits **410**_a_ and **410**_b_ of FIGS. **4**A and **4**B.

The double star string voltage balancing circuit **810**_b_ is respectively connected to the DC voltage source strings **802**_b_, **804**_b_ and **806**_b_, in a generally redundant manner, to balance the voltages generated by the DC voltage source strings **802**_b_, **804**_b_ and **806**_b_. The double star string voltage balancing circuit **810**_b_ is respectively connected between the DC voltage sources strings **802***b*, **804***b*, and **806** and includes two inductors **827***b* (L_1) and **837***b* (L_2) and six switches forming a double star configuration.

Also, the double star string voltage balancing circuit **810***b* can similarly overcome limitations of a relatively large number of components and physical location differences of circuit topology location associated with the closed loop string voltage balancing circuits **510***a* and **510***b* and the complementary string voltage balancing circuits **601***a* and **601***b*, such as illustrated in FIGS. **5**A, **5**B, **6**A and **6**B, respectively, for example.

A first part of the double star string voltage balancing circuit **810***b* includes three IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **822***b*, **824***b* and **826***b*. Use of IGBT type switches for the switches **822***b*, **824***b* and **826***b* can allow for relatively higher switching frequencies and can reduce harmonic content, for example. The double star string voltage balancing circuit **810***b* also includes the inductor **827***b* (L_1) that can act to filter out ripples in the individual string currents respectively controlled by the switches **822***b*, **824***b* and **826***b* flowing in the corresponding DC voltage source strings **802***b*, **804***b* and **806***b*.

The first part of the double star string voltage balancing circuit **810***b* also includes three capacitors **803***b* (C_1), **805***b* (C_2) and **807***b* (C_3) which are also shared with and included in a second part of the double star string voltage balancing circuit **810***b*. The capacitor **803***b* (C_1) is connected to the switch **822***b* and is associated with the first DC voltage source string **802***b* to balance the voltage generated by the first DC voltage source string **802***b*. The capacitor **805***b* (C_2) is connected to the switch **824***b* and is associated with the second DC voltage source string **804***b* to balance the voltage generated by the second DC voltage source string **804***b*. The capacitor **807***b* (C_3) is connected to the switch **826***b* and is associated with the third DC voltage source string **806***b* to balance the voltage generated by the third DC voltage source string **806***b*. In some embodiments, the switches **822***b*, **824***b* and **826***b* have reverse blocking capability or, as illustrated, can be connected to series diodes or to series type diode arrangements **821***b*, **823***b* and **825***b* configured to block reverse current to provide a reverse blocking capability, for example.

A second part of the double star string voltage balancing circuit **810***b* includes three IGBT type semiconductor switches as can be reverse blocking switches (e.g., valves) **832***b*, **834***b* and **836***b*. Use of IGBT type switches for the switches **832***b*, **834***b* and **836***b* can allow for relatively higher switching frequencies and can reduce harmonic content, for example. The double star string voltage balancing circuit **810***b* also includes the inductor **837***b* (L_2) respectively connected to each of the switches **832***b*, **834***b* and **836***b*. The inductor **837***b* (L_2) can act to filter out ripples in the individual string currents respectively controlled by the switches **832***b*, **834***b* and **836***b* flowing in the corresponding DC voltage source strings **802***b*, **804***b*, and **806***b*.

Also the second part of the double star string voltage balancing circuit **810***b* also includes the three capacitors **803***b* (C_1), **805***b* (C_2) and **807***b* (C_3), which are also shared with and included in the first part of the double star string voltage balancing circuit **810***b*. The capacitor **803***b* (C_1) is connected to the switch **832***b* and is associated with the first DC voltage source string **802***b* to balance the voltage generated by the first DC voltage source string **802***b*. The capacitor **805***b* (C_2) is connected to the switch **834***b* and is associated with the second DC voltage source string **804***b* to balance the voltage generated by the second DC voltage source string **804***b*. The capacitor **807***b* (C_3) is connected to the switch **836***b* and is associated with the third DC voltage source string **806***b* to balance the voltage generated by the third DC voltage source string **806***b*. In some embodiments, the switches **832***b*, **834***b* and **836***b* have reverse blocking capability or, as illustrated, can be connected to series diodes or to series type diode arrangements **831***b*, **833***b* and **835***b* configured to block reverse current to provide a reverse blocking capability, for example.

In the double star string voltage balancing circuit **810***b*, the switches **822***b*, **824***b* and **826***b* and the switches **832***b*, **834***b* and **836***b* in addition to being IGBT type semiconductor switches, can also include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

For example, for purposes of illustration, the first DC voltage source string **802***b* can generate a 100 kV output voltage V_1, the second DC voltage source string **804***b* can generate an 80 kV output voltage V_2 and the third DC voltage source string **806***b* can generate a 90 kV output voltage V_3. Therefore, the double star string voltage balancing circuit **810***b* can balance or substantially balance the DC voltage source strings **802***b*, **804***b* and **806***b* output voltage at 90 kV, for example. In such case, the voltage across the capacitor **803***b* (C_1) is −10 kV, the voltage across the capacitor and **805***b* (C_2) is 10 kV, the voltage across the capacitor **807***b* (C_3) is 0 kV, for example.

The duty ratios or duty cycles, δ_1-δ_6, of the corresponding switches **822***a*, **824***a* and **826***a* and the switches **832***a*, **834***a* and **836***a* in the double star string voltage balancing circuit **810***a* and of the corresponding switches **822***b*, **824***b* and **826***b* and the switches **832***b*, **834***b* and **836***b* in the double star string voltage balancing circuit **810***b* are controlled to get the desired output DC voltage across the load terminals, such as the loads **830***a* and **830***b* of the power generation system. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense. The voltage unbalance in the lines can be translated into a negative potential on a corresponding capacitor, a positive potential on a corresponding capacitor or a zero potential on a corresponding capacitor to provide the voltage balancing, for example.

The double star string voltage balancing circuits **810***a* and **810***b* respectively illustrated in FIGS. **8**A and **8**B can be generalized an extended to any number of a plurality of DC voltage source strings connected in parallel. It is noted that the voltage balancing circuits and topologies as illustrated in FIGS. **8**A and **8**B, and as described herein, can be extended to architectures including n parallel connected DC converters for a corresponding power generation system having a plurality of DC voltage source strings to be balanced, as can depend on the use or application, and should not be construed in a limiting sense.

Also, when compared with the single star string voltage balancing circuits **710***a* and **710***b*, respectively illustrated in FIGS. **7**A and **7**B, the double star string voltage balancing circuits **810***a* and **810***b*, respectively illustrated in FIGS. **8**A and **8**B, can include the identical three switches and an inductor in each of a first star arrangement and a second star arrangement, for example. An advantage of the double star string voltage balancing circuits **810***a* and **810***b* is that, while the double star string voltage balancing circuits **810***a* and

810*b* each include double the number of switches and inductors used from that of the single star string voltage balancing circuits **710***a* and **710***b*, the double star string voltage balancing circuits **810***a* and **810***b* can reduce the switches current to half or substantially half of that of the single star string voltage balancing circuits **710***a* and **710***b*, as well as can reduce the capacitor sizes used, for example.

In some embodiments, such redundancy, such as in the double star string voltage balancing circuits **810***a* and **810***b*, can therefore lower the device rating as is illustrated in Table 1 (e.g., power rating of the double star balancing circuit is reduced to approximately 50%). As is illustrated in Table 1, a double star balancing converter topology can be relatively advantageous based on a comparison index that considers the number of components and device rating, for example.

TABLE 1

Comparative Analysis of Balancing Converter Topologies
Three Lines String Voltage Balancing Converter
(Note: Full load is the total current from the three lines)

	Closed Ring	Single Star	Double Star
Switches			
# of switches	6	3	6
Max current/full load (%)	66.67%	100%	50%
Average Current/Max Current	0.5	0.33	0.33
Max (Average Current/Full load (%))	33.33%	33.33%	16.67%
# of switches *Max Current/Full load (%)	4	3	3
Inductors			
# of inductors	3	1	2
Max Current/Full load (%)	66.67%	100%	100%
# of inductors *Max Current/Full load (%)	2	1	1
Capacitors			
# of capacitors	3	3	3
Index (Inductors, switches, capacitors)	9 = 4 + 2 + 3	7 = 3 + 1 + 3	7 = 3 + 1 + 3
Ranking based on index (worst to best)	Closed Ring	Single Star	Double Star

FIG. **9** illustrates a general schematic diagram of an embodiment of power generation system with DC voltage source strings connected in parallel including an embodiment of a DC voltage balancing circuit in an open ring balancing converter configuration. FIG. **9** illustrates an embodiment of a power generation system **900** that utilizes an open ring string voltage balancing circuit **902**, such as illustrated in FIG. **9**.

The power generation system **900** includes three unbalanced DC voltage source strings **910**, **920** and **930**, such as of PV panels or wind turbines. As illustrated, the DC voltage sources strings **910**, **920** and **930** are connected in parallel, and are also connected in parallel to a load **960** to which an output voltage is provided.

The open ring string voltage balancing circuit **902** is connected between the DC voltage source strings **910**, **920** and **930**. Also, the open ring voltage balancing circuit **902**, in the embodiment of FIG. **9**, includes a topology similar to the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B. The open ring string voltage balancing circuit **902** can therefore be considered as an extension of the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B.

The open ring string voltage balancing circuit **902** includes reverse blocking switches (e.g., valves) **942** and **944** and an inductor **947** connected between switches **942** and **944**, the switches **942** and **944** dividing the inductor **947** current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **942** and **944** have reverse blocking capability or, as illustrated, can be connected to series diodes or to series diode type arrangements **943** and **945** configured to block reverse current to provide a reverse blocking capability, for example.

The open ring string voltage balancing circuit **902** also includes reverse blocking switches (e.g., valves) **952** and **954** and an inductor **957** connected between switches **952** and **954**, the switches **952** and **954** dividing the inductor **957** current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **952** and **954** have reverse blocking capability or, as illustrated, can be similarly connected to series diodes or to series diode type arrangements **953** and **955** configured to block reverse current to provide a reverse blocking capability, for example.

The open ring string voltage balancing circuit **902** is connected between the DC voltage source strings **910**, **920** and **930** to balance the voltages generated by the DC voltage source strings **910**, **920** and **930**. The open ring string voltage balancing circuit **902** also includes thee capacitors **946**, **948** and **950**. The capacitor **946** is connected in series with the DC voltage source string **910** and is also connected to the switch **942**. The capacitor **948** is connected in series with the DC voltage source string **920** and is also connected to the switch **944** and the switch **952**. The capacitor **950** is connected in series with the DC voltage source string **930** and is also connected to the switch **954**.

In the open ring string voltage balancing circuit **902**, the switches **942**, **944**, **952** and **954** include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

Also, as illustrated in FIG. **9**, the power generation system **900** also includes a resistor **912** in series with an inductor **914** connected in series with the capacitor **946** and the DC voltage source string **910**, a resistor **922** in series with an inductor **924** connected in series with the capacitor **948** and the DC voltage source string **920** and a resistor **932** in series with an inductor **934** connected in series with the capacitor **950** and the DC voltage source string **930**. The resistors **912**, **922** and **932** respectively in series with the inductors **914**, **924** and **934** can act as a filter, such as to minimize or reducing a ripple current, for example, in the power generation system **900**.

The duty ratios or duty cycles, δ_1-δ_4, of the corresponding switches **942**, **944**, **952** and **954** in the open ring string voltage balancing circuit **902** are controlled to get the desired output DC voltage across the load terminals, such as at the load **960** of the power generation system. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense. The voltage unbalance in the lines can be translated into a negative potential on a corresponding capacitor, a positive potential on a corresponding capacitor or a zero potential on a corresponding capacitor to provide the voltage balancing, for example.

For example, for purposes of illustration, the DC voltage source string **910** can generate a 100 kV output voltage V_1, the DC voltage source string **920** can generate a 90 kV output voltage V_2 and the DC voltage source string **930** can generate an 80 kV output voltage V_3. However, in the power generation system **900**, the open ring string voltage balancing circuit **902** illustrates voltage balancing for the three DC voltage source strings **910**, **920** and **930** with essentially two voltage balancing circuits that form the open ring string voltage balancing circuit **902**, using an open ring type configuration.

While the open ring string voltage balancing circuit **902** can provide voltage balancing of DC voltage source strings in a power generation system in some operating conditions, the open ring string voltage balancing circuit **902**, due to its open ring configuration, does not necessarily provide voltage balancing for all operating conditions in a power generation system. In this regard, if the DC voltages generated by the three DC voltage source strings **910**, **920** and **930** are 100 kV, 90 kV and 80 kV, respectively, then the left capacitor **946** potential should be −10 kV, the right capacitor **960** potential should be 10 kV, and the middle capacitor potential should be 0 kV.

However, in this example, the open ring string voltage balancing circuit **902** cannot operate to effectively balance the voltages unless the voltages of its groupings of two capacitors have an opposite sign. Another problem that can arise in voltage balancing using the open ring string voltage balancing circuit **902** with the open right type configuration is that the ratings of the switches, such as transistors, are typically not equal. In this regard, in the open ring string voltage balancing circuit **902** the two middle switches, such as transistors, are feeding one DC voltage source line and the two outer switches, such as transistors, each feed one DC voltage source line, for example.

The open ring string voltage balancing circuit **902** respectively illustrated in FIG. **9** can, for suitable applications, be generalized an extended to any number of a plurality of DC voltage source strings connected in parallel, for those applications to which is applicable. It is noted that the voltage balancing circuits and topologies as illustrated in FIG. **9**, and as described herein, can be extended to architectures including n parallel connected DC converters for a corresponding power generation system having a plurality of DC voltage source strings to be balanced, as can depend on the use or application, and should not be construed in a limiting sense.

Therefore, as described herein, embodiments of string voltage balancing converters can provide all or substantially all the benefits of microinverters (AC or DC) at a relatively reduced complexity and/or cost. Embodiments of string voltage balancing converters can also be relatively superior to AC microinverters, particularly for use in higher voltage utility scale systems, for example.

Also, embodiments of string voltage balancing converters can be relatively superior to DC microinverters because, in some cases, power generation systems using DC micro inverters typically still require voltage balancing when more strings are connected in parallel. In such cases, one solution can be to overrate each of the DC microinverters to account for any voltage drops in any string, such as is described for large scale wind farm architectures in S. Lundberg, "Evaluation of wind farm layouts," EPE Journal, vol. 19, no. 1, pp. 157-169 (March 2004), the entirety of which in incorporated by reference herein as part of this specification.

However, overrating DC microinverters can come at a relatively significant complexity and/or cost. In various embodiments using string balancing voltage converters can substantially reduce a need to overrate each individual inverter (or groups of inverters) in a power generation system. In this regard, embodiments of string voltage balancing converters can be arranged in topologies that can allow for integration into central inverter architectures or can serve as an add-on to such architectures, for example.

In some embodiments, using string voltage balancing converters can be cost effective. For example, Table 2 presents a cost analysis based on published figures (from December 2009) for a 7 kW system, which can be considered a sizable rooftop PV installation. The price information used for Table 2 was based on that from a PV distributor, AEE Solar. Although the total cost of central converter solution is relatively the lowest, the costs of the central converter solution do not account for any of the system accessories, wiring, protection equipment, etc.

As is illustrated in Table 2, a multiple string system that utilizes string voltage balancing converters can cost somewhat more than the central converter system, but less than a system that utilizes microinverters. In this regard, additional components configured to perform string voltage balancing are typically relatively less costly and less complex than another converter, and can also be integrated into central inverter architectures or can serve as an add-on to such architectures, for example.

TABLE 2

Economic Study of a 7 kW System

Topologies	Inverter	Integrated Module	Total Cost
Central converter	$5,470	Not applicable	$ 5,470
String voltage balancing converters	2 × $3,580	Not applicable	$ 7,160
Microinverter	Not applicable	40 × $288	$11,520

Also, as described, embodiments of string voltage balancing converters can be applicable to various series connection of DC voltage sources that are placed in parallel combinations, such as for PV applications, wind energy applications (e.g., wind turbine collection grids), battery cells, capacitor banks, and the like.

As mentioned, embodiments of string voltage balancing power converters, as can include embodiments of voltage balancing circuits and topologies, can be combined with embodiments of current balancing circuits and topologies of various configurations for power generation electrical systems to balance DC voltage source strings that are placed in parallel. For example, balancing the current in each of DC voltage sources of a DC voltage source string, such as a string of PV panels or wind turbines, etc., can be beneficial as can enhance relatively efficient generation of output power in power generation systems.

In this regard, series connection of PV panels or wind turbines, etc. to build up voltage can force the panels to hold the same current which can possibly result in a decreased efficiency if the PV panels are of different parameters (irradiance) and, hence, the DC voltage source string(s) including such PV panels do not necessarily operate at its maximum power point (mpp).

One solution is to assist in operating the DC voltage source strings DC voltage sources, such as PV panels, at a maximum power point (mpp) is connect each DC voltage source, such as a PV panel to a DC converter to enhance the PV panel's ability to deliver a maximum available power, then connect the DC converters in a suitable way (series, parallel, etc.).

Another solution to assist in operating the DC voltage source strings DC voltage sources, such as PV panels, at a maximum power point (mpp) is to connect the DC voltage source strings DC voltage sources, such as PV panels, in series and attach them to a balancing circuit to bypass the required difference current, such as illustrated in FIG. **11**A and FIG. **11**B, such as can be beneficial in partial shading conditions, for example. Such process is referred to as differential power processing (DPP) series balancing. Implementing embodiments of DPP series balancing to DC voltage sources in DC voltage source strings in a power generation system having a plurality of DC voltage source strings can enhance the DC voltage source's, such as a PV panel's ability, to deliver a maximum available power and, therefore, can enhance each DC voltage source strings ability to generate a maximum power.

FIG. **11**A illustrates a general schematic diagram of an embodiment of power generation system **1100***a* including an embodiment of a DPP current balancing circuit **1110***a* as can be used in a power generation system of a plurality of DC voltage source strings to balance the current between series connected DC voltage sources, such as PV arrays, in a DC voltage source string. For exemplary purposes, the power generation system **1100***a* illustrates a single DC voltage source string having a plurality of DC voltage sources or modules, such as PV panels. The DC voltage source string in the power generation system **1100***a* includes DC voltage sources or modules ("DC voltage source module(s)") **1120***a*, **1222***a* and **1224***a*.

The DPP current balancing circuit **1110***a* includes a plurality of switches **1132***a*, **1134***a* and **1136***a* respectively connected with the DC voltage source modules **1120***a*, **1222***a* and **1224***a*, each of the switches **1132***a*, **1134***a* and **1136***a* is respectively associated with a diode **1131***a*, **1133***a* and **1135***a*, to control bypass of a difference current. An inductor **1137***a* is connected between the DC voltage source modules **1120***a* and **1122***a* and connected between the switches **1132***a* and **1134***a* to carry a difference current and induce a difference voltage. An inductor **1139***a* is connected between the DC voltage source modules **1122***a* and **1124***a* and connected between the switches **1134***a* and **1136***a* to carry a difference current and induce a difference voltage. A DC voltage V_c is provided across a capacitor **1140***a* connected in parallel with the DC voltage source modules **1120***a*, **1222***a* and **1224***a*.

The switches **1132***a*, **1134***a* and **1136***a* can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **11**B illustrates a general schematic diagram of another embodiment of a power generation system **1100***b* including an embodiment of a DPP current balancing circuit **1110***b* as can be used in a power generation system of a plurality of DC voltage source strings to balance the current between series connected DC voltage source modules, such as PV arrays in a DC voltage source string. For exemplary purposes, the power generation system **1100***b* illustrates a single DC voltage source string having a plurality of DC voltage source modules, such as PV panels. The DC voltage source string in the power generation system includes DC voltage source modules **1120***b*, **1222***b* and **1224***b*.

The DPP current balancing circuit **1110***b* includes a plurality of switches **1132***b*, **1134***b* and **1136***b* each respectively connected with the DC voltage source modules **1120***b*, **1222***b* and **1224***b* to control bypass of a difference current. Inductors **1121***b*, **1123***b* and **1125***b* are respectively connected in series with the DC voltage source modules **1120***b*, **1222***b* and **1224***b* to filter a ripple current. A DC voltage V_c is provided across a capacitor **1140***b* connected in parallel with the DC voltage source modules **1120***b*, **1222***b* and **1224***b*.

The switches **1132***b*, **1134***b* and **1136***b* can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

As between the embodiment of the DPP current balancing circuit **1110***a* of FIG. **11**A and the embodiment of the DPP current balancing circuit **1110***b* of FIG. **11**B, the embodiment of the DPP current balancing circuit **1110***a* can be relatively better in that is can more easily be replaced or incorporated into power generation systems, as well as includes a smaller number of inductors of a reduced rating, for example.

FIG. **11**C illustrates a general schematic diagram of an embodiment of a power generation system **1100***c* including an embodiment of a DPP current balancing circuit **1110***c* corresponding to the DPP current balancing circuit **1110***a* of FIG. **11**A to illustrate switching states of the switches of the current balancing circuit and difference currents for differential power processing as can be used in a power generation system of a plurality of DC voltage source strings to balance the current between series connected DC voltage source modules, such as PV arrays, in a DC voltage source string.

For exemplary purposes, the power generation system **1100***c* similarly illustrates a single DC voltage source string having a plurality of DC voltage source modules, such as PV panels. The DC voltage source string in the power generation system **1100***c* includes DC voltage source modules **1120***c*, **1222***c* and **1224***c*. The DC voltage source module **1120***c* generates a voltage V_1 and has a current i_l, DC voltage source module **1122***c* generates a voltage V_2 and has a current i_2, and DC voltage source module **1124***c* generates a voltage V_3 and has a current i_3.

The DPP current balancing circuit **1110***c* includes a plurality of switches **1132***c*, **1134***c* and **1136***c* respectively connected with the DC voltage source modules **1120***c*, **1222***c* and **1224***c*, each of the switches **1132***c*, **1134***c* and **1136***c* is respectively associated with diodes **1131***c*, **1133***c* and **1135***c*, to control bypass of a difference current. An inductor **1137***c* (L_{12}) passing a current i_{13} is connected between the DC voltage source modules **1120***c* and **1122***c* and connected between the switches **1132***c* and **1134***c* to pass a difference current and induce a difference voltage. An inductor **1139***c* (L_{23}) passing a current i_{23} is connected between the DC voltage sources modules **1122***c* and **1124***c* and connected between the switches **1134***c* and **1136***c* to pass a difference current and induce a difference voltage. A DC voltage V_c is provided across a capacitor **1140***c* connected in parallel with the DC voltage source modules **1120***c*, **1222***c* and **1224***c*. A load **1150***c* is connected across the capacitor **1140***c*.

The switches **1132***c*, **1134***c* and **1136***c* similarly can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense. Also, the switches are controlled so as to control values of the currents flowing in the inductances and, therefore, values of currents carried by the DC voltage source modules can differ from one another, for example.

In the embodiment of the power generation system **1100***c,* in modeling and control of the DPP current balancing circuit **1110***c* for current balancing of the individual DC voltage source modules **1120***c,* **1122***c* and **1124***c,* the DPP current balancing circuit **1110***c* has three switching states S_1, S_2 and S_3. FIG. **11**D illustrates a general schematic diagram **1100***d* of the first switching state S_1, FIG. **11**E illustrates a general schematic diagram **1100***e* of the second switching state S_2 and FIG. **11**F illustrates a general schematic diagram **1100***f* of a third switching state S_3 in an embodiment of DPP current balancing circuit **1110***c* of FIG. **11**C.

Continuing with reference to FIGS. **11**C-**11**F, the switching states S_1, S_2 and S_3 complete a switching period Δt as follows:

$$\Delta t = T = \frac{1}{fswitching}, \tag{1}$$

where **S1**+**S2**+**S3**=1. Also, the voltages induced by and the currents flowing across the inductors **1137***c* (L_{12}) **1139***c* (L_{23}) for the switching states **S1**, **S2** and **S3** can be determined according to the following relations:

$$L_{12}\frac{\Delta i_{12}}{\Delta t} = (S_2+S_3)V_1 + S_1(V_1 - V_c) = (S_1+S_2+S_3)V_1 - S_1V_c, \tag{2}$$

$$L_{23}\frac{\Delta i_{23}}{\Delta t} = -(S_1+S_2)V_3 + S_3(V_c - V_3), \tag{3}$$

$$\Delta i_{12} = \frac{T}{L_{12}}(V_1 - S_1V_c) = -(S_1+S_2+S_3)V_3 + S_3V_c \text{ and} \tag{4}$$

$$\Delta i_{23} = \frac{T}{L_{23}}(-V_3 + S_3V_c). \tag{5}$$

Further, for the switching states S_1, S_2 and S_3 at steady state:

$$\Delta i_{12} = \Delta i_{23} = 0 \rightarrow S_1 = \frac{V_1}{V_c},\ S_3 = \frac{V_3}{V_c}. \tag{6}$$

Also, for the switching states S_1, S_2 and S_3 at transient state:

$$\Delta i_{12} \propto \Delta S_1, \Delta i_{23} \propto \Delta S_3 \text{ and} \tag{7}$$

$$\Delta S_1+\Delta S_2+\Delta S_3=0. \tag{8}$$

At an initial moment of time, it is assumed to have $V_1=V_2=V_3$, approximately, for the switching states S_1, S_2 and S_3. Then $S_1=S_2=S_3=1/3$, as can correspond to the duty ratios or duty cycles for the switches **1132***c,* **1134***c* and **1136***c,* for example. To reach the reference i_{12}, $i_{23} \rightarrow S_1$, S_2, S_3 are slightly changed and finally can reach their equilibrium states according to the actual voltages V_1, V_2, V_3, and $\Delta S_1 \propto -$(required increase Δi_{12}), ΔS_3 a (required increase Δi_{23}) and $\Delta S_2=0-\Delta S_1-\Delta S_3$.

FIG. **12** illustrates a general schematic diagram of an embodiment of a controller **1200** illustrating a process for implementing the switching states S_1, S_2 and S_3 of the DPP current balancing circuit **1110***c* of FIG. **11**C for differential power processing as can be used in a power generation system to balance the current between series connected DC voltage sources, such as PV arrays in a DC voltage source string. The controller can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense.

The controller **1200** includes or implements summation modules or circuits **1210**, **1214**, **1220**, **1224**, **1230** and **1232** for respectively receiving and positively/negatively summing the reference ("ref") and the actual ("act") values of the currents i_{12} and i_{23} and the switching states and deltas (Δ) of the switching states S_1, S_2 and S_3, such as of the DPP current balancing circuit **1110***c*. The controller **1200** also includes proportional-integral (PI) controllers **1212** and **1222** to implement control of the switching states S_1, S_2 and S_3, as can be in conjunction with other processes, operations, systems and controllers, embodiments of the DPP current balancing processes and operations, such as can be implemented by or in conjunction with the generalized system **1000** of FIG. **10**, as can include, constitute or perform the functions and operations of the controller **1200**, for example. In this regard, the controller **1200** can be implemented in a Simulink model as implemented by the embedded Matlab® function entitled "Saturation function (Adaptive gain)", for example.

In the control process implemented by the controller **1200**, typically before ΔS_1, ΔS_2 and ΔS_3 are added to the switching states S_1, S_2 and S_3, the delta values for the switching states the switching states S_1, S_2 and S_3 are checked to verify that any of ΔS_1, ΔS_2 and

$$\Delta S_3 > -\frac{1}{3},$$

for example. This verification is done because ($\Delta S+\Delta S_{initial}$) must be >0 since it is a duty cycle or duty ratio, for example. Also, the duty cycles or duty ratios corresponding to the switching states of the switches in various embodiments of the DPP current balancing circuits and processes, can vary, as dependent on the use or application or on the number of switches or circuit configurations, for example, and should not be construed in a limiting sense.

Also, in an embodiment of the control process for DPP current balancing implemented by the controller **1200**, if any of ΔS_1, ΔS_2 and ΔS_3 is determined to be smaller than $-1/3$, then the following relation (9) will set ΔS_{min} to $-1/3$ and also scale the other ΔS to maintain the rule that $\Delta S_1+\Delta S_2+\Delta S_3=0$ as in relation (8):

$$\Delta S = \frac{\Delta S * \frac{1}{3}}{|\min \Delta S|}. \tag{9}$$

Further, in controlling the switching states S_1, S_2 and S_3, the switches can be gated, such as the switches **1132**, **1134***c* and **1136***c,* as can be transistors. Also, the diodes respectively corresponding to the switches, such as the diodes **1131***c,* **1133***c* and **1135***c,* can be correspondingly antiparallel gated for current balancing of the DC voltage source modules, such as DC voltage source modules **1120***c,* **122***c* and **1124***c*. The gating of the switches and the antiparallel gating of the corresponding diodes can be based on the following relations that indicate an on-state for the corresponding switches, such as the switches **1132**_c_, **1134**_c_ and **1136**_c_, also thereby indicate an off-state for the diodes corresponding to the switches:

$$t_1=S_2(i_{12}>0)+S_3(i_{12}+i_{23}>0), \quad (10)$$

$$t_2=S_1(i_{12}+i_{23}<0)+S_3(i_{23}>0) \text{ and} \quad (11)$$

$$t_3=S_1(i_{12}+i_{23}<0)+S_2(i_{23}<0). \quad (12)$$

Above, t_1 corresponds to the first switch **1132**_c_, t_2 corresponds to the second switch **1134**_c_ and t_3 corresponds to the third switch **1136**_c_. Irrespective of the inequalities of the values of the difference currents, the switches, such as the switches **1132**_c_, **1134**_c_ and **1136**_c_, as can be transistors, can be gated. Such gating of the switches can reduce the diode voltage drop (synchronized rectification) and can decrease conduction losses, for example.

The duty ratios or duty cycles, δ_1-δ_3, of the corresponding switches **1132**_c_, **1134**_c_ and **1136**_c_ of the DPP current balancing circuit **1110**_c_ are controlled such that each DC voltage source module **1120**_c_, **1122**_c_ and **1124**_c_ can carry or substantially carry the current at max power (I_{mpp}) which will differ from one DC voltage source module to another and that the voltage across each DC voltage source module will be a voltage at a maximum power (V_{mpp}), such as by control of the switching states S_1, S_2 and S_3 of the corresponding switches **1132**_c_, **1134**_c_ and **1136**_c_, as described. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **13** illustrates a general schematic diagram of an embodiment of a voltage and current balancing circuit **1300**. The voltage and current balancing circuit **1300** includes a plurality of DPP current balancing circuits **1350**, **1360** and **1370**, each similar to the DPP current balancing circuit **1110**_c_, as described, for differential power processing to balance the current between series connected DC voltage source modules, such as PV arrays, in a corresponding DC voltage source string.

Each of the DPP current balancing circuits **1350**, **1360** and **1370** operate in a similar manner to that of the DPP voltage balancing circuit **1110**_c_, as described, in relation to FIGS. **11**C-**11**F and **12**. The voltage and current balancing circuit **1300** also includes an integrated embodiment of a string voltage balancing circuit **1310** that is similar to and operates in a similar manner to the voltage balancing circuits **400**_a_ and **400**_b_, as described, to balance the voltage of a plurality DC voltage source strings in a power generation system. Positive and negative potentials for the voltage and current balancing circuit **1300** are indicated at **1380** and **1382**, respectively. An advantage of the configuration and topology of the voltage and current balancing circuit **1300** is that it can provide expandability and flexibility in that the DC voltage source strings can be from different manufacturing sources and can be integrated in the circuit topology.

The DPP current balancing circuit **1350** is associated with a first DC voltage source string having DC voltage source modules **1352**_a_, **1352**_b_, **1352**_c_ and **1352**_d_. The DPP current balancing circuit **1350** includes a plurality of switches **1154**_a_, **1354**_b_, **1354**_c_ and **1154**_d_ respectively connected with the DC voltage source modules **1352**_a_, **1352**_b_, **1352**_c_ and **1352**_d_, each of the switches **1354**_a_, **1354**_b_, **1354**_c_ and **1354**_d_ is respectively associated with diodes **1355**_a_, **1355**_b_, **1355**_c_ and **1355**_d_, to control bypass of a difference current. An inductor **1356**_a_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1352**_a_ and **1352**_b_ and connected between the switches **1354**_a_ and **1354**_b_. An inductor **1356**_b_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1352**_b_ and **1352**_c_ and connected between the switches **1354**_b_ and **1354**_c_. An inductor **1356**_c_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1352**_c_ and **1352**_d_ and connected between the switches **1354**_c_ and **1354**_d_. A DC voltage V_{c1} is provided across a capacitor **1358** connected in parallel with the DC voltage source modules **1352**_a_, **1352**_b_, **1352**_c_ and **1352**_d_.

Similarly, the DPP current balancing circuit **1360** is associated with a second DC voltage source string having DC voltage source modules **1362**_a_, **1362**_b_, **1362**_c_ and **1362**_d_. The DPP current balancing circuit **1360** includes a plurality of switches **1164**_a_, **1364**_b_, **1364**_c_ and **1164**_d_ respectively connected with the DC voltage source modules **1362**_a_, **1362**_b_, **1362**_c_ and **1362**_d_, each of the switches **1364**_a_, **1364**_b_, **1364**_c_ and **1364**_d_ is respectively associated with diodes **1365**_a_, **1365**_b_, **1365**_c_ and **1365**_d_, to control bypass of a difference current. An inductor **1366**_a_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1362**_a_ and **1362**_b_ and connected between the switches **1364**_a_ and **1364**_b_. An inductor **1366**_b_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1362**_b_ and **1362**_c_ and connected between the switches **1364**_b_ and **1364**_c_. An inductor **1366**_c_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1362**_c_ and **1362**_d_ and connected between the switches **1364**_c_ and **1364**_d_. A DC voltage V_{c2} is provided across a capacitor **1368** connected in parallel with the DC voltage source modules **1362**_a_, **13 62**_b_, **1362**_c_ and **1362**_d_.

Also, the DPP current balancing circuit **1370** is associated with a third DC voltage source string having DC voltage source modules **1372**_a_, **1372**_b_, **1372**_c_ and **1372**_d_. The DPP current balancing circuit **1370** includes a plurality of switches **1174**_a_, **1374**_b_, **1374**_c_ and **1174**_d_ respectively connected with the DC voltage source modules **1372**_a_, **1372**_b_, **1372**_c_ and **1372**_d_, each of the switches **1374**_a_, **1374**_b_, **1374**_c_ and **1374**_d_ is respectively associated with diodes **1375**_a_, **1375**_b_, **1375**_c_ and **1375**_d_, to control bypass of a difference current. An inductor **1376**_a_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1372**_a_ and **1372**_b_ and connected between the switches **1374**_a_ and **1374**_b_. An inductor **1376**_b_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1372**_b_ and **1372**_c_ and connected between the switches **1374**_b_ and **1374**_c_. An inductor **1376**_c_ passing a difference current and inducing a difference voltage is connected between the DC voltage source modules **1372**_c_ and **1372**_d_ and connected between the switches **1374**_c_ and **1374**_d_. A DC voltage V_{c3} is provided across a capacitor **1378** connected in parallel with the DC voltage source modules **1372**_a_, **1372**_b_, **1372**_c_ and **1362**_d_.

Continuing, as to the string voltage balancing circuit **1310**, the string voltage balancing circuit **1310** is connected between the three DC voltage source strings associated respectively associated with the DPP current balancing circuits **1350**, **1360** and **1370**. Also, the string voltage balancing circuit **1310** would typically be connected in a closed ring type configuration, similar to that illustrated in FIGS. **5**A and **5**B, as described, a portion of which is illustrated in FIG. **13**. The string voltage balancing circuit **1310** can therefore be considered as an extension of the string voltage balancing circuits **410***a* and **410***b* of FIGS. **4**A and **4**B.

The string voltage balancing circuit **1310** includes reverse blocking switches (e.g., valves) **1311** and **1312** and an inductor **1317** connected between switches **1311** and **1312**, the switches **1311** and **1312** dividing the inductor **1317** current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **1311** and **1312** have reverse blocking capability or, as illustrated, can be connected to series diodes or to series diode type arrangements **1313** and **1314** configured to block reverse current to provide a reverse blocking capability, for example.

The string voltage balancing circuit **1310** also includes reverse blocking switches (e.g., valves) **1321** and **1322** and an inductor **1327** connected between switches **1321** and **1322**, the switches **1321** and **1322** dividing the inductor **1327** current between the two lines, such as according to their operating operation point, for example. In some embodiments, the switches **1321** and **1322** have reverse blocking capability or, as illustrated, can be similarly connected to series diodes or to series diode type arrangements **1323** and **1324** configured to block reverse current to provide a reverse blocking capability, for example.

The string voltage balancing circuit **1310** is connected between the DC voltage source strings associated with the DPP current balancing circuits **1350**, **1360** and **1370** to balance the voltages generated by the DC voltage source strings. The string voltage balancing circuit **1310** also includes three capacitors **1315**, **1325** and **1335**. The capacitor **1315** is connected in series to the switch **1354***d* of the DPP current balancing circuit **1350** and to the DC voltage source module **1352***d* and is also connected to the switch **1311**. The capacitor **1325** is connected in series to the switch **1364***d* of the DPP current balancing circuit **1360** and to the DC voltage source module **1362***d* and is also connected to the switch **1312** and the switch **1321**. The capacitor **1335** is connected in series to the switch **1374***d* of the DPP current balancing circuit **1370** and to the DC voltage source module **1372***d* and is also connected to the switch **1322**.

The switches of the voltage and current balancing circuit **1300** can include any of various suitable switches, such as metal-oxide semiconductor field effect transistor (MOSFET) switches, insulated-gate bipolar transistor (IGBT) semiconductor switches, various types of transistor-type switches, or any another suitable components, as can depend on the use or application, and should not be construed in a limiting sense.

The duty ratios or duty cycles, δ, of the corresponding switches of the DPP current balancing circuits **1350**, **1360** and **1370** are controlled such that each DC voltage source module can carry or substantially carry the current at max power (I_{mpp}) which will differ from one DC voltage source module to another and that voltage across each DC voltage source module will be a voltage at a maximum power (V_{mpp}), such as by control of the switching states of the switches, similar to that described in relation to FIGS. **11**C-**11**F and **12**. Also, the duty ratios or duty cycles, δ, of the corresponding the switches in the string voltage balancing circuit **1310** are controlled to get the desired output DC voltage across the load terminals of the power generation system. Such control can be provided by a suitable maximum power point control (MPP) process, such as can be implemented by a computer processor in Matlab®, such as can be implemented by the generalized system **1000** of FIG. **10**, for example, as can depend on the use or application, and should not be construed in a limiting sense.

FIG. **14**A illustrates a graph **1400***a* of power (watts (W)) versus time (s) for PV panel characteristics at different insolation levels for differential power processing in current balancing DC voltage source modules of series connected DC voltage sources. The differential power processing concept for extracting a maximum power from DC voltage source modules, such as PV arrays, during partial shading conditions can be applied such that each DC voltage source module can carry a current at maximum power (I_{mpp}) which can differ from one DC voltage source module to another. As illustrated form the graph **1400***a*, the voltage across each DC voltage source module is a voltage at maximum power (V_{mpp}), which is almost constant for all insolation levels. In this regard, by direct parallel connection of DC voltage source strings in the DPP current balancing, it is also possible to use the differential converters as voltage balancers for DC voltage source modules, which can reduce a need for additional balancing circuits, for example.

FIG. **14**B, FIG. **14**C, FIG. **14**D, FIG. **14**E, FIG. **14**F and FIG. **14**G illustrate graphs of simulation results respectively comparing voltage, current, overall string current, total output voltage, total output current and total output power, versus time, for a two DC voltage source string current balancing circuit topology, similar to the current balancing topology of FIG. **11**C implemented for each of two DC voltage source strings for differential power processing to balance the current between series connected DC voltage source modules, such as PV arrays, in a corresponding DC voltage source string.

In the simulation, two parallel DC voltage source strings of a PV array consisting of a total combined six DC voltage source modules, each DC voltage source string including three DC voltage source modules, to provide a 3 by 2 PV array as shown in Table 3, the DC voltage source modules being referred to as "module" in the table. The DC voltage source modules in the simulation had an open circuit voltage of 22.2 V, a voltage at maximum power of 17.2 V, a short circuit current of 5.45 A, and a current at maximum power of 4.95 A at an insolation level of 1000 watts/meter^2 (W/m^2).

TABLE 3

PV Array (3 × 2)	
DC Voltage Source Sting 1	DC Voltage Source Sting 2
Module 1	Module 4
Module 2	Module 5
Module 3	Module 6

In the simulation, to demonstrate and validate the DPP current balancing concept as to direct parallel connection of DPP-based (series balancing based) strings, the following case was tested using Matlab®/Simulink, as set forth in Table 4.

TABLE 4

Test Case Parameters for Simulation

	Insolation (W/m^2)	V_{mpp} (V)	I_{mpp} (A)	P_{mpp} (W)
Module 1	1000	17.2	5	85
Module 2	300	17.2	1.39	24
Module 3	800	17.2	4	68
Module 4	1000	17.2	5	85

TABLE 4-continued

Test Case Parameters for Simulation

	Insolation (W/m^2)	V_{mpp} (V)	I_{mpp} (A)	P_{mpp} (W)
Module 5	1000	17.2	5	85
Module 6	800	17.2	4	68

Based on the above data and parameters to extract a maximum power for a corresponding PV array, a power of 415 W was delivered at load at voltage of 51.6 V, and a current of 8.04 A. The corresponding simulation results for the abovementioned data are illustrated in the graphs of 1400*b*-**1400***g* of FIGS. **14**B through **14**G. From the results illustrated in the graphs of FIGS. **14**B-**14**G, it is evident that DPP current balancing was successfully applied, and a relatively exact MPP was extracted after a certain searching period.

FIG. **14**B illustrates the graph **1400***b* of simulation results comparing voltage (V) versus time (s). In the graph **1400***b* it can be seen that the voltage V_1-V_6 for the modules **1-6** indicates DPP current balancing for each of the modules **1-6** of the DC voltage source strings **1** and **2**.

FIG. **14**C illustrates the graph **1400***c* of simulation results comparing current (A) versus time (s). In the graph **1400***c* it can be seen that the current i_1-i_6 of the modules **1-6** indicates DPP current balancing for each of the modules **1-6** of the DC voltage source strings **1** and **2**.

FIG. **14**D illustrates the graph **1400***d* of simulation results comparing overall string current (A) versus time (s). In the graph **1400***d*, it can be seen that the current i_{sc1} for the first DC voltage source string and the current i_{sc2} for the second DC voltage source string indicates DPP current balancing for each of the modules **1-6** of the DC voltage source strings **1** and **2**.

FIG. **14**E illustrates the graph **1400***e* of simulation results comparing total output, voltage (V) versus time (s). In the graph **1400***e*, it can be seen that the total output voltage indicates DPP current balancing for each of the modules **1-6** of the DC voltage source strings **1** and **2**.

FIG. **14**F illustrates the graph **1400***f* of simulation results comparing total output current (A) versus time (s). In the graph **1400***f*, it can be seen that the total output current indicates DPP current balancing for each of the modules **1-6** of the DC voltage source strings **1** and **2**.

FIG. **14**G illustrates the graph **1400***g* of simulation results comparing total output power (W) versus time (s). In the graph **1400***g*, it can be seen that the total output power indicates DPP current balancing for each of the modules **1-6** of the DC voltage source strings **1** and **2**.

Those skilled in the art will appreciate that in some embodiments, additional or alternative components and/or modules can be used to perform string voltage balancing conversion. Disclosed systems and circuits can be utilized in AC power generation systems. In addition, disclosed systems and circuits can be used for systems in which at least some single and/or string sources are connected in series. Further, in some embodiments at least some DC source making up a DC voltage source string can be connected in parallel. Additional system components can be utilized, and disclosed system components can be combined or omitted. Depending on the embodiment, certain of the steps described above can be removed, others can be added.

Conditional language used herein, such as, among others, "can," "might," "may," "e.g.," and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not necessarily have to include, certain features, elements and/or states. Also, the terms "comprising," "including," "having," and the like are synonymous and are used inclusively, in an open-ended fashion, and do not exclude additional elements, features, acts, operations, and so forth. Also, the term "or" is used in its inclusive sense (and not in its exclusive sense) so that when used, for example, to connect a list of elements, the term "or" means one, some, or all of the elements in the list.

For example, the various components illustrated in the figures can be implemented in dedicated hardware or on ASIC or on a field programmable gate array (FPGA), for example. Firmware and/or software modules can be additionally or alternatively used. Also, the features and attributes of the specific embodiments disclosed above can be combined in different ways to form additional embodiments, all of which fall within the scope of the present disclosure.

Although the present disclosure provides certain desirable embodiments and applications, other embodiments that are apparent to those of ordinary skill in the art, including embodiments which do not provide all of the features and advantages set forth herein, are also within the scope of this disclosure.

It is to be understood that the present invention is not limited to the embodiments described above, but encompasses any and all embodiments within the scope of the following claims.

We claim:

1. An apparatus for voltage balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system, comprising:

at least one string voltage balancing circuit, each string voltage balancing circuit comprising:

at least two reverse blocking switches each adapted to control a current flowing in and an output voltage of one or more corresponding DC voltage source strings; and

at least two capacitors each communicatively connected to a corresponding at least one reverse blocking switch and communicatively connected in series with a corresponding one of the plurality of DC voltage source strings, each capacitor being adapted to construct a voltage difference for a corresponding one of the plurality DC voltage source strings,

wherein the at least one string voltage balancing circuit selectively adjusts an output voltage of each of the DC voltage source strings by selectively controlling a current flowing in corresponding ones of the plurality of DC voltage source strings to selectively adjust a voltage constructed across corresponding ones of the at least two capacitors to balance the output voltage for each of the DC voltage source strings to be substantially the same output voltage.

2. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein the at least one string voltage balancing circuit further comprises:

at least one inductor communicatively connected to least two reverse blocking switches adapted to minimize a ripple current flowing to the two reverse blocking switches, the current flowing in the inductor being divided by the at least two reverse blocking switches to flow the divided current into corresponding ones of the plurality of DC voltage source strings.

3. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **2**, wherein the at least two reverse blocking switches comprise a switch selected from the group consisting of a transistor, a metal-oxide semiconductor field effect transistor (MOSFET) and an insulated-gate bipolar transistor (IGBT).

4. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein the at least two reverse blocking switches comprise a switch selected from the group consisting of a transistor, a metal-oxide semiconductor field effect transistor (MOSFET) and an insulated-gate bipolar transistor (IGBT).

5. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein duty ratios of the at least two reverse blocking switches are controlled to construct the voltage difference for corresponding ones of the plurality DC voltage source strings to balance the output voltage for each of the DC voltage source strings to be substantially the same output voltage.

6. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **5**, wherein a sum of the duty ratios of the at two reverse blocking switches is substantially equal to one (1).

7. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein the at least one string voltage balancing circuit further comprises:

at least two diodes respectively arranged in series with corresponding ones of the at least two reverse blocking switches adapted to control a direction of current flow.

8. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein

the at least one string voltage balancing circuit comprises a closed loop voltage balancing configuration, and

the closed loop configuration comprises:

at least six reverse blocking switches adapted to control a current flowing in and an output voltage of at least three corresponding DC voltage source strings, and

at least three capacitors each communicatively connected to at least a corresponding pair of reverse blocking switches and to a corresponding one of the DC voltage source strings.

9. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein

the at least one string voltage balancing circuit comprises a complimentary string voltage balancing configuration, and

the complimentary string voltage balancing configuration comprises:

at least a pair of said string voltage balancing circuits, each pair of said string voltage balancing circuits being arranged in opposing relation at opposite ends of a corresponding group of three DC voltage source strings adapted to control a current flowing in and an output voltage of the group of the three corresponding DC voltage source strings,

wherein a capacitor from each of said pair of said string voltage balancing circuits is communicatively connected to a same corresponding one of the DC voltage source strings of the group of three DC voltage source strings, the capacitors connected to the same corresponding DC voltage source string being adapted to construct a voltage difference for the said same DC voltage source string.

10. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein

the at least one string voltage balancing circuit comprises a single star string voltage balancing configuration, and

the single star string voltage balancing configuration comprises:

at least three reverse blocking switches each associated with a respective one of a corresponding plurality of DC voltage source strings adapted to control a current flowing in and an output voltage of the respective one of the DC voltage source strings, and

at least three capacitors each communicatively connected to a respective one of the DC voltage source strings to which the corresponding respective reverse blocking switch is communicatively connected.

11. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **10**, wherein the single star voltage balancing configuration further comprises:

an inductor communicatively connected to each of the plurality of reverse blocking switches adapted to minimize a ripple current flowing to the reverse blocking switches, the current flowing in the inductor being divided by the reverse blocking switches to flow the divided current into corresponding ones of the plurality of DC voltage source strings.

12. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, wherein

the at least one string voltage balancing circuit comprises a double star string voltage balancing configuration, and

the double star string voltage balancing configuration comprises:

a first group and a second group each of at least three reverse blocking switches, a reverse blocking switch from each of the first and the second group being respectively associated with a respective one of a corresponding plurality of DC voltage source strings adapted to control a current flowing in and an output voltage of the respective one of the DC voltage source strings, and

at least three capacitors each communicatively connected to a respective one of the DC voltage source strings to which the corresponding respective reverse blocking switch from the first group and the respective reverse blocking switch from the second group is communicatively connected.

13. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **12**, wherein the double star voltage balancing configuration further comprises:

a pair of inductors, one of said pair of inductors being communicatively connected to the first group of reverse blocking switches and the other of the pair of inductors being communicatively connected to the second group of reverse blocking switches, the pair of inductors adapted to minimize a ripple current flowing to the reverse blocking switches, the current flowing in the inductor communicatively connected to the first group of reverse blocking switches being divided by the reverse blocking switches of the first group to flow the divided current into corresponding ones of the plurality of DC voltage source strings, and the current flowing in the inductor communicatively connected to the second group of reverse blocking switches being divided by the reverse blocking switches of the second group to flow the divided current into corresponding ones of the plurality of DC voltage source strings.

14. The apparatus for voltage balancing a plurality of parallel arranged DC voltage source strings according to claim **1**, further comprising:

a controller including a processor to control operation of the at least one voltage balancing circuit to selectively adjust the output voltage of each of the DC voltage source strings by selectively controlling a current flowing in corresponding ones of the plurality of DC voltage source strings to selectively adjust a voltage constructed across corresponding ones of the at least two capacitors to balance the output voltage for each of the DC voltage source strings to be substantially the same output voltage.

15. A method for voltage balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system, comprising the steps of:

controlling by a controller including a processor an operation of at least one string voltage balancing circuit to selectively adjust an output voltage of each of a plurality of DC voltage source strings by selectively controlling a current flowing in corresponding ones of the plurality of DC voltage source strings;

selectively controlling by the controller a current flowing in each of the plurality of DC voltage source strings by controlling operation of at least two reverse blocking switches associated with a corresponding at least one voltage balancing circuit, each reverse blocking switch associated with a corresponding one of the plurality of DC voltage source strings; and

selectively adjusting by the controller a voltage difference for at least two capacitors associated with a corresponding at least one voltage balancing circuit to selectively adjust a voltage constructed across corresponding ones of the at least two capacitors to balance the output voltage for each of the DC voltage source strings to be substantially the same output voltage.

16. The method for voltage balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system according to claim **15**, further comprising the step of:

controlling by the controller including a processor an operation of differential power processing (DPP) to adjust respective currents flowing through each of a plurality of series connected DC voltage source modules respectively forming corresponding ones of the plurality of DC voltage source strings by a plurality of reverse blocking switches communicatively connected to the corresponding ones of the series connected DC voltage source modules to balance the current between corresponding ones of the series connected DC voltage source modules.

17. The method for voltage balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system according to claim **16**, wherein

the controller controls the operation of differential power processing (DPP) to adjust the respective currents flowing through each of the plurality of series connected DC voltage source modules such that each DC voltage source module can substantially carry a current at a maximum power (I_{mpp}) different from another DC voltage source module in the corresponding ones of the plurality of DC voltage source strings, and

a voltage generated by each DC voltage source module based on the adjusted current corresponds to a voltage at a maximum power (V_{mpp}).

18. An apparatus for current balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system, comprising:

at least one differential power processing (DPP) current balancing circuit, each DPP current balancing circuit comprising:

a plurality of reverse blocking switches communicatively connected to a plurality of series connected DC voltage source modules respectively forming corresponding ones of the plurality of DC voltage source strings to control currents respectively flowing through each of the communicatively connected series connected DC voltage source modules; and

a plurality of inductors communicatively connected to the series connected DC voltage source modules and to the plurality of reverse blocking switches to induce a corresponding voltage based on the flow of the respective controlled currents to balance a current between corresponding ones of the series connected DC voltage source modules to adjust the respective currents flowing through each of the plurality of series connected DC voltage source modules.

19. The apparatus for current balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system according to claim **18**, further comprising:

a controller including a processor to control operation of the plurality of reverse blocking switches for the differential power processing (DPP) operation to control adjusting the respective controlled currents flowing through each of the plurality of inductors to the series connected DC voltage source modules respectively forming corresponding ones of the plurality of DC voltage source strings to balance the current between the corresponding series connected DC voltage source modules.

20. The apparatus for current balancing a plurality of parallel arranged direct current (DC) voltage source strings in a power generation system according to claim **19**, wherein

the controller controls the operation of differential power processing (DPP) to adjust the respective currents flowing through each of the plurality of series connected DC voltage source modules such that each DC voltage source module can substantially carry a current at a maximum power (L_{mpp}) different from another DC voltage source module in the corresponding ones of the plurality of DC voltage source strings, and

a voltage generated by each DC voltage source module based on the adjusted current corresponds to a voltage at a maximum power (V_{mpp}).

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